

# Power Quality Solutions for Industrial Customers



A Guidebook by the California Energy Commission

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# CITATIONS

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# 1

## INTRODUCTION

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The electric utility environment has never been one of constant voltage and frequency. Until recently, most electrical equipment could operate satisfactorily during expected deviations from the nominal voltage and frequency supplied by the utility. In the modern industrial facility, many electrical and electronic devices have been incorporated into the automated processes. No doubt that programmable logic controllers (PLCs), adjustable-speed drives (ASDs), energy efficient motors, CNC machines, and other power electronic devices increase productivity, increase the quality of products, and decrease the cost to customers of those products. However, they also increase the potential for problems with electrical compatibility because they are not as forgiving of their electrical environment as earlier technologies. As a result of this recent increase in equipment vulnerability, the owners of industrial processes have experienced unexplained process interruptions and unplanned equipment shutdowns.

The source of these compatibility problems may not be readily apparent to the industrial maintenance personnel. Likewise, personnel may not be familiar with the solutions that are available to increase the reliability of process equipment. The California Energy Commission (CEC) has prepared this guidebook for utility power quality engineers and their industrial customers. The technical guidelines herein will help you identify the sources of incompatibility problems as well as low-cost solutions to resolve those problems.

Many process interruptions can be prevented. With a little knowledge of power quality issues, owners of industrial processes can learn to identify causes of electrical disturbances and take action to prevent their recurrence. This guidebook identifies the most common electrical disturbances that can trouble industrial processes. It also discusses process equipment that are vulnerable to these disturbances and solutions that make the equipment compatible with the electrical environment.

Contrary to common belief, the utility-supplied electricity is not the cause of all power-related process interruptions. In fact, studies by the Electric Power Research Institute (EPRI) indicate that as much as 80% of all power quality problems can be attributed to inadequate electrical grounding or wiring, or to interactions between loads within the premises. This guidebook also discusses grounding issues encountered in industrial power distribution systems as well as electromagnetic interference (EMI).



# 2

## HOW ELECTRICAL DISTURBANCES AFFECT INDUSTRIAL CUSTOMERS

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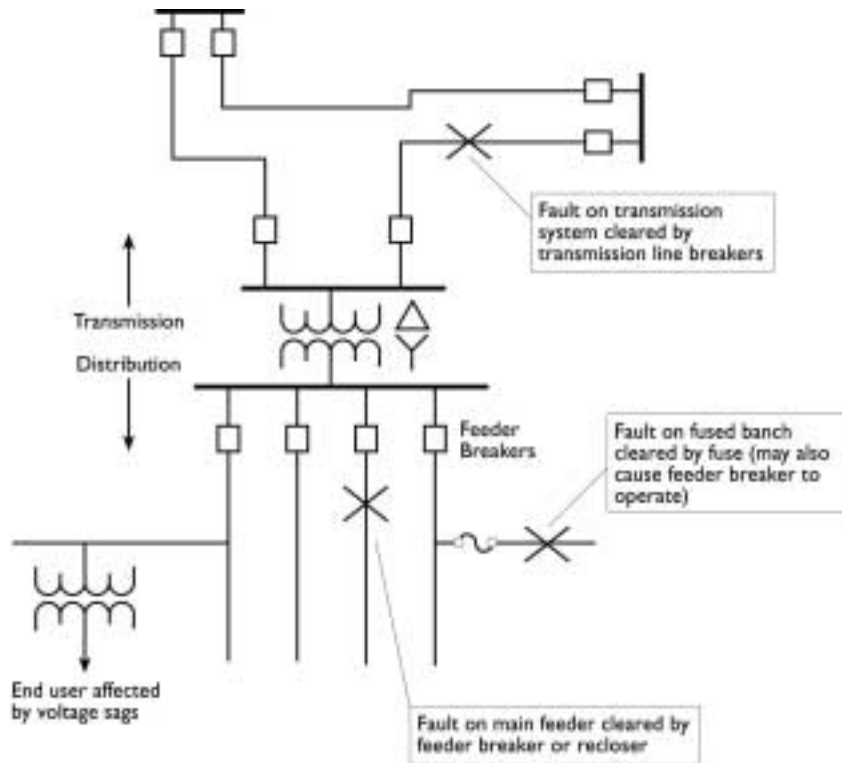
There are several electrical disturbances that commonly affect industrial processes. This section discusses the disturbances that have the greatest effect on industrial processes: voltage sags, capacitor switching, surges, and harmonics.

### 2.1 Voltage Sags

A voltage sag is defined as a decrease in RMS voltage magnitude lasting from 0.5 to 30 cycles. Voltage sags are usually caused by a fault in the utility transmission or distribution system. Power-line faults can be caused by animals on lines, a car striking a utility pole, or lightning strikes to power lines. Although proper maintenance, grounding, and arresters can minimize the number of faults, faults can never be eliminated.

Most of the faults in the utility system are cleared by the operation of protective devices. Substation breakers are typically set up with a relay that opens momentarily during a fault to allow the fault to clear. The effects of a temporary fault and relay operation on an end user vary, depending on the relative location of that user in the system.

If a fault occurs on a supplying distribution feeder, as shown in Figure 2-1, a customer would experience a brief interruption. All other customers on adjacent feeders would experience a voltage sag, the duration of which depends upon the clearing time of the protective device. The depth of the sag depends upon how close the customer is to the fault location, resistance at the fault, and the available fault current. On other hand, a fault on the transmission system would cause a sag to all the customers downstream of that location.

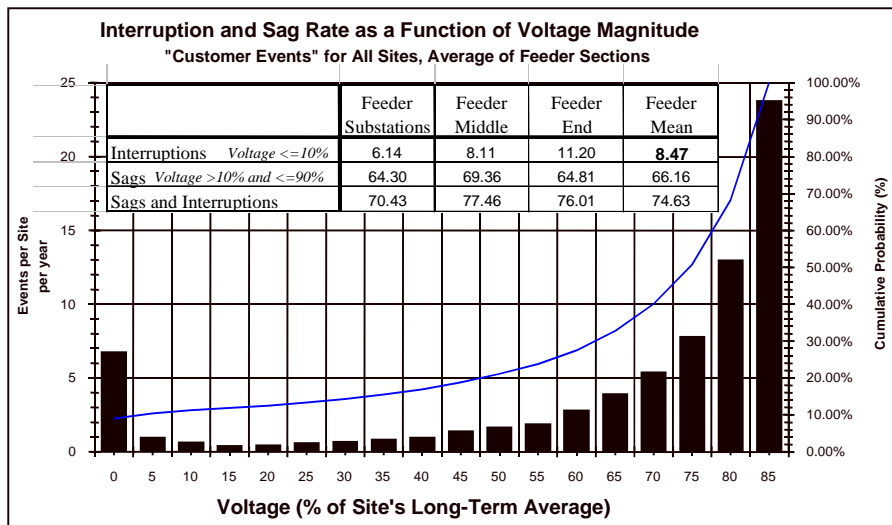


**Figure 2-1. Example Distribution System Showing Fault Location and Affect on the Customer**

### **2.1.1 Statistics on Voltage Sags**

Voltage sags that have the potential to affect industrial plants and process equipment are common. The Electric Power Research Institute (EPRI) Distribution Power Quality (DPQ) Monitoring Project has collected data from distribution systems around the country. Figure 2-2 summarizes the results of that three-year project, which collected samples from over 250 sites. This data provides an estimate of the typical magnitude and frequency of voltage sags and momentary interruptions (lasting 0.5 cycles to 3 seconds) that may be expected at a given site.

As can be seen from Figure 2-2, an average of 66 voltage sags between 10% and 90% is expected at a given site per year. Also, the average number of momentary interruptions at a given site is between 8 and 9 per year. However, it should be noted that at any given site, the actual sag rate may vary depending on the configuration of the distribution and transmission system, customer density, geographical location, and utility preventive-maintenance policy.



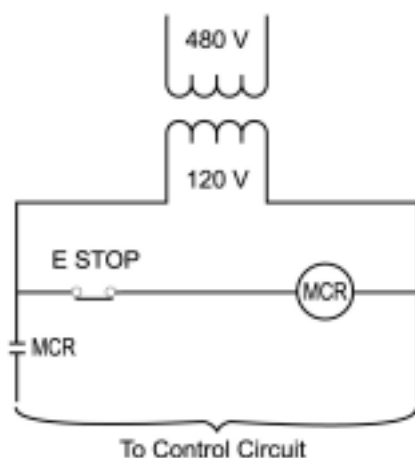
**Figure 2-2. Summary of the Sag and Interruption Data from the DPQ Study**

## 2.1.2 Equipment Vulnerable to Voltage Sags

Motor loads drive most industrial processes. The tripping of a motor due to a voltage sag will often be the cause of process shutdowns. For example, the loss of an air compressor due to a voltage sag will interrupt the supply of compressed air required to operate the process equipment. As a result, many process lines in the facility will be shut down due to the loss of this auxiliary equipment. However, it is important to understand that most motor trips initiated by a voltage sag are caused by the response of the controls and not the motor starters and drives.

### 2.1.2.1 Relays

If your process controls use a 120-VAC relay in the emergency-stop circuit of the control circuit, you can expect up to 20 shutdowns a year due to voltage sags. The reason for this vulnerability is the design of a typical emergency-stop circuit, as shown in Figure 2-3.

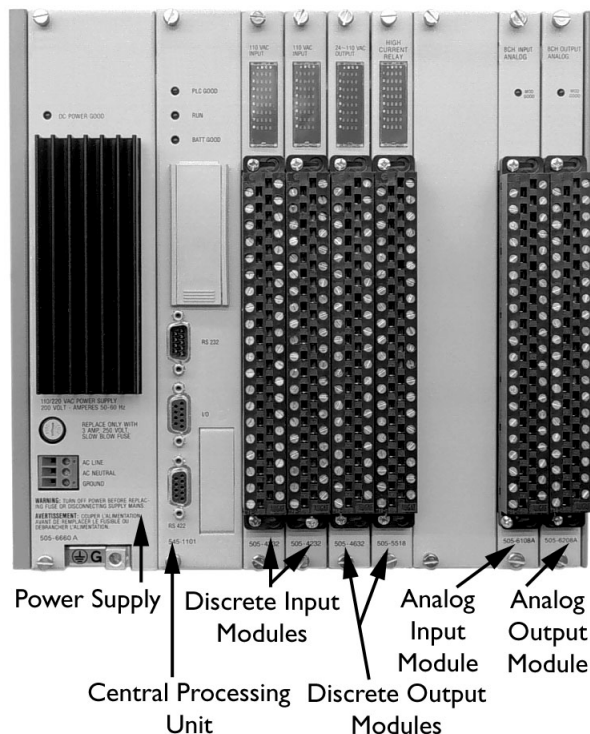


**Figure 2-3. Typical Emergency-Stop Circuit**

The master control relay (MCR) in this circuit is normally energized. Pushing the emergency-stop switch drops out the relay and opens the normally open contact, which provides power to the remaining control circuit. This type of fail-safe circuit shuts down the process if the MCR fails. If the MCR is a sensitive relay, it will drop out during a sufficiently deep sag just as the actuation of the emergency-stop switch would drop the relay. The process controlled by the MCR will shut down, and the operator may have no evidence that a voltage sag was the cause of the shutdown.

### 2.1.2.2 Programmable Logic Controllers

The programmable logic controller (PLC) is basically a hardened industrial computer that has multi-channel input and output modules to control process devices. Figure 2-4 shows the basic elements of a typical PLC. The elements consist of the power supply, the central process unit (CPU), and input and output (I/O) modules.



**Figure 2-4. Typical Programmable Logic Controller**

Voltage sags can affect any of the PLC components. Typical of most power supplies, a PLC power supply takes a 120-VAC input and provides the required low-voltage DC output to components. The ride-through characteristics of the power supply depend mainly upon the size of the ripple control and energy-storage capacitor used in the switch-mode power supply.

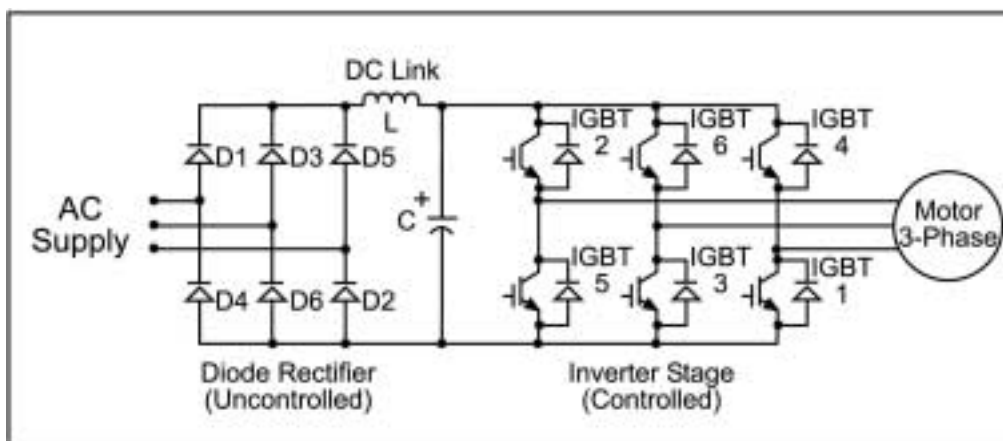
The I/O system forms the interface between the field devices and the controller. Input devices such as pushbuttons, limit switches, and auxiliary contacts are hardwired into the input terminals of the controller. These signals are usually discrete signals that sense the presence or absence of voltage at the terminal (for example, a logical 1 or 0). When the voltage at the terminal is 120 volts, the CPU interprets this signal as a logical 1. When the voltage at the terminal is zero, the CPU interprets this signal as a logical 0. When the voltage sags to 60% of nominal for 6 cycles, how will the CPU interpret the resulting signal? The voltage at which the CPU interprets the signal as a 1 or 0 is called the threshold voltage. There is no standard for the threshold voltage level, which is why this threshold varies widely from model to model. The response of a PLC to a voltage sag can vary from extremely vulnerable to very robust. Facility or process owners should therefore understand the response of the particular PLCs that are installed in the process. More importantly, they should understand the response of a particular PLC to voltage sags when specifying new equipment.

### 2.1.2.3 Adjustable-Speed Drives

Adjustable-speed drives (ASDs) have grown in popularity in large part due to the energy savings that they offer. The ASD can control process flow by varying the motor speed. Prior to the introduction of ASDs into the process industry, motors operated at full speed and flow was controlled by the use of dampers or flow-control valves. With the advancements in power electronics technology, the cost, size, and complexity of inverters are decreasing, making ASDs more affordable and highly prevalent in process environments.

Voltage sags can generally affect an ASD in two ways. The first and most likely way is through the dropout of a control relay, as discussed in the section on relays. The dropout of a master control relay used in emergency-stop circuits can cause the drive to shut down and disrupt the process.

A second way that the ASD can be disrupted by a voltage sag is by an undervoltage trip of the DC link. Figure 2-5 shows the location of the DC link in the most common type of ASD used in the industry for controlling the speed of induction motors: the pulse-width-modulated (PWM) voltage source inverter AC drive.



**Figure 2-5. DC Link in a Typical Pulse-Width-Modulation (PWM) Adjustable-Speed Drive**

A PWM ASD consists of a rectifier stage that converts the incoming AC voltage to a DC voltage across a DC-bus capacitor. The inverter stage then converts the DC voltage to an AC voltage of a desired frequency and magnitude. When the ASD is exposed to a voltage sag, the voltage at the DC bus decreases. When the DC bus reaches the undervoltage trip point (typically set anywhere between 75 and 85 percent of the nominal DC bus voltage), the drive will trip on undervoltage.

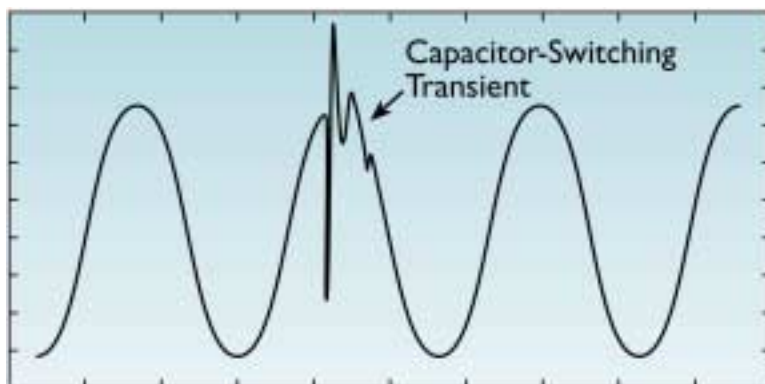
## 2.2 Utility Transients

A transient is defined in IEEE 1100-1999 as a subcycle disturbance in the AC waveform that is evidenced by a sharp, brief discontinuity of the waveform. Transients can be categorized as either impulsive or oscillatory. Lightning surges are the most common cause of impulsive transients on the utility system. Capacitor switching is the most common cause of oscillatory transients. Both types of transients can affect industrial equipment.

### 2.2.1 Capacitor Switching

Utilities routinely switch capacitors onto the distribution system to maintain the system voltage when the load increases. Some utilities switch on capacitors at a specific time of day based on historical load profiles. Others may switch capacitors on as monitors detect the increase in load or drop in system voltage.

Switching on a capacitor can create an oscillatory transient on the system voltage, as shown in Figure 2-6. When a capacitor is initially switched onto the distribution system, the voltage across the capacitor terminals rapidly falls to zero because the voltage across a capacitor cannot change instantaneously. The system voltage will increase as the distance from the capacitor banks increases. As the capacitor charges, the voltage oscillates so that a voltage overshoot rises to between 1.3 p.u. to 1.4 p.u. of the original system voltage. This oscillation will be reflected in the distribution voltage at an industrial site.

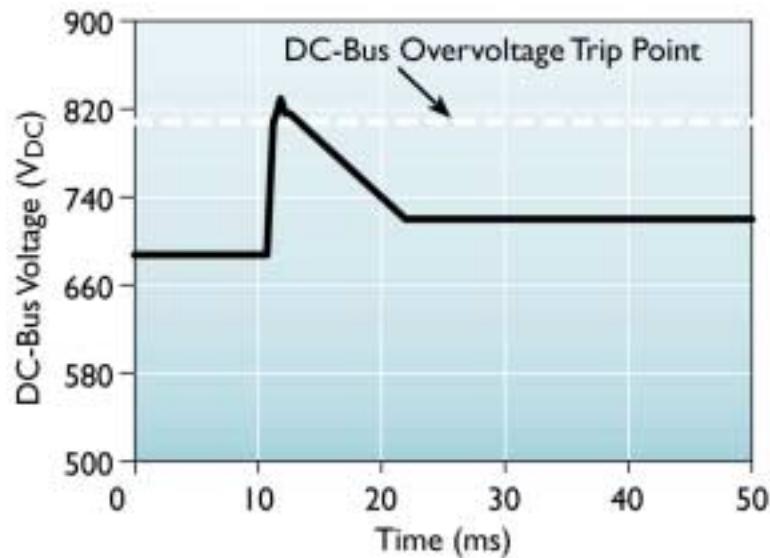


**Figure 2-6. Typical Capacitor-Switching Transient**

Most equipment will have sufficient ride-through capacity to withstand the drop in voltage caused by this transient. The voltage overshoot, however, can affect such equipment as ASDs.



The oscillation in the AC voltage will affect the voltage level of the DC bus. Figure 2-7 shows an example of a capacitor-switching transient causing the DC bus to exceed the overvoltage trip point.

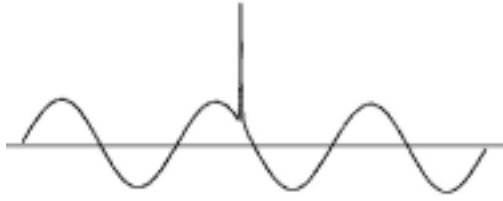


**Figure 2-7. DC-Bus Voltage of Adjustable-Speed Drive During a Capacitor-Switching Transient**

Without transient monitors, it can be difficult to be certain that the cause of an ASD trip was a capacitor-switching transient. However, there are two characteristics that can be clues that an ASD has tripped due to a capacitor-switching transient. The first clue is that the ASD controls indicate that the drive tripped due to an overvoltage. Because capacitor switching causes many of the overvoltage transients in the distribution system, it is a likely cause of overvoltage ASD trips. The second clue that your ASD has tripped due to a capacitor-switching transient is that a pattern of tripping has been noticed. Because many utilities switch capacitors at the same time every day, vulnerable ASDs may also trip at the same time every day. Check with your local utility to determine if the utility has a capacitor-switching schedule that coincides with the time that ASDs are tripping.

### **2.2.2 Impulsive Transients (Surges)**

An impulsive transient is typically characterized by a sudden change in frequency not related to the power frequency, large amounts of energy, and fast rise and decay times. These transients are typically caused by lightning or system faults. Figure 2-8 shows an example of an impulsive transient.



**Figure 2-8. Impulsive Transient**

An impulsive transient can be very damaging to a wide range of industrial equipment. The damage is caused by the high level of voltage and energy that is applied to equipment that is not rated for that level of energy. Electronic equipment is particularly susceptible to impulsive transients because they are normally exposed to low levels of power.

### 2.3 Harmonics

Harmonic distortion of the voltage and current in an industrial facility is caused by the operation of nonlinear loads and devices on the power system. A nonlinear load is one that does not draw sinusoidal current when a sinusoidal voltage is applied. Examples on nonlinear loads are arcing devices such as arc furnaces, saturable devices such as transformers, and power electronic equipment such as adjustable-speed drives and rectifiers.

High harmonic currents can have several negative effects on a facility. High levels of distortion can lower power factors, overheat equipment, and lead to penalties from the local utility for exceeding recommended limits. Each of these effects can result in higher cost to the facility.

Harmonic currents increase the volt-amperes required for a load without increasing the watts. Because true power factor is equal to the watts divided by the volt-amperes, any increase in volt-amperes without a corresponding increase in watts will lower the power factor. A lower power factor will affect industrial facilities in two ways. Losses inside the facility will increase due to the higher level of current required to perform the work. Utilities will also charge a penalty if the power factor falls below a predetermined level. Both of these will increase utility bills.

Overheating of transformers is another problem associated with harmonic currents. ANSI/IEEE Standard C57 series states that a transformer can only be expected to carry its rated current if the current distortion is less than 5%. If the current distortion exceeds this value, then some amount of derating is required. The overheating is caused primarily by the higher eddy-current losses inside the transformer than were anticipated by the designer. The overheating can be avoided by either derating the transformer or by specifying a “k-rated” transformer that is designed for the higher levels of eddy currents.

Another effect of harmonic currents on the power system is the overheating of neutral wires in wye-connected circuits. This effect occurs because the third harmonic and any multiples thereof do not cancel in the neutral as do the other harmonic currents. The result is a large 180-Hz current in the neutral conductor if there are significant nonlinear loads connected to the wye source. Usually the higher multiples of the third harmonic are of small magnitude. The attendant increase in the RMS value of current, however, can cause excessive heating in the neutral wire.

This potential for overheating can be addressed by oversizing neutral conductors or reducing nonlinear currents with filters.

Some utilities impose limits on the amount of harmonic current that can be injected onto the utility system. This is done to ensure that relatively harmonic-free voltage is supplied to all customers on the distribution line. IEEE Standard 519-1992 recommends limits for harmonics for both utilities and customers. At the point of common coupling between the utility and the utility customer, limits are recommended for individual harmonics as well as the total harmonic distortion of the current. The recommended levels vary depending on the size of the load with respect to the size of the power system and also upon the voltage at the point of common coupling. The standard also recommends limits on the voltage harmonics supplied by the utility.



# 3

## MOTOR ISSUES

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In a typical process industry, the primary loads are motor-driven. Low-voltage and medium-voltage induction motors, medium-voltage synchronous motors, and motors controlled by electronic AC or DC drives make up the motor loads in a plant. Motors ranging from a few horsepower to thousands of horsepower—directly connected to the utility system or connected through a variable-speed drive—provide a variety of process and auxiliary functions.

Motor failures can have a significant affect on facility operation and unscheduled downtime. Many times, premature failure of motors is associated with system voltage unbalances. Failures are also related to motors controlled by adjustable-speed drives. An understanding of how motors are affected by these conditions can be valuable in preventing motor failures.

### 3.1 Voltage Unbalance

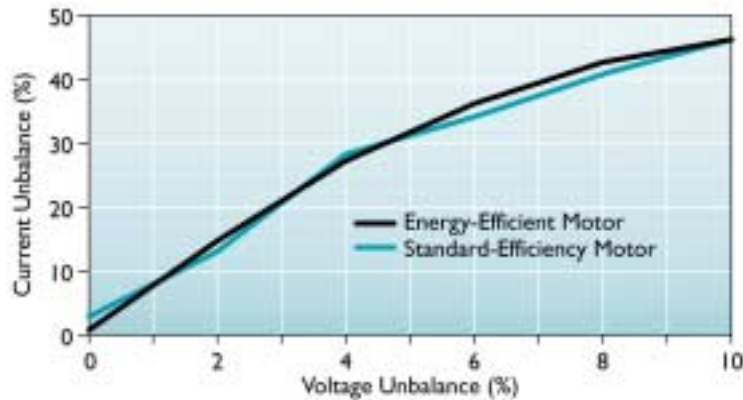
A voltage unbalance exists when phase voltages at the point of utilization are unequal. There are many possible causes of voltage unbalance, including the malfunction of automatic power-factor-correction equipment and voltage regulators in the utility distribution lines, unevenly distributed single-phase loads in a facility, high-impedance connections, and an unbalanced transformer bank. If the unbalance cannot be traced to an internal distribution element or to unbalanced single-phase loads in the facility, the local utility may need to assist by evaluating the voltage unbalance in the distribution system and the condition of voltage-regulation devices.

An unbalanced three-phase voltage causes three-phase motors to draw unbalanced current, which can cause the rotor of a motor to overheat. In fact, the temperature rise caused by unbalanced current is much greater than the rise caused by balanced current.

According to ANSI Standard *C84.1, Electric Power Systems and Equipment – Voltage Ratings (60 Hertz)*, about 98 percent of surveyed electrical power-supply systems are within three percent voltage unbalance, with 66 percent of the systems at one percent or less. ANSI *C84.1* recommends that electric power systems have no more than three percent voltage unbalance when measured at the revenue meter during no-load conditions.

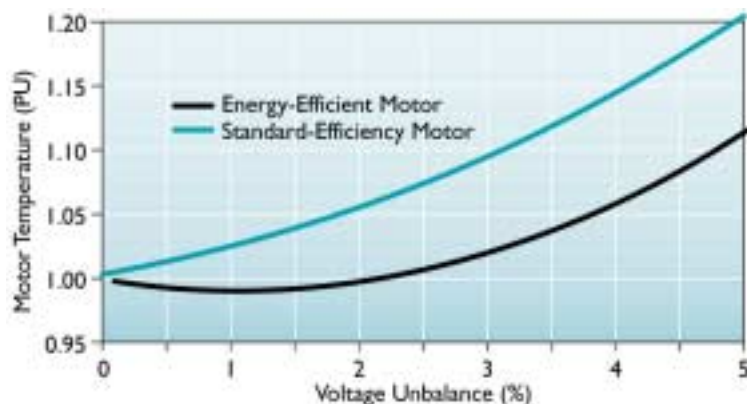
The rule of thumb for a standard-efficiency induction motor is that for every one percent of voltage unbalance, the resulting percent of current unbalance will be about five to six times as much. However, high-efficiency motors, especially Design-E motors, generally have a lower resistance. Therefore, the current unbalance resulting from a given voltage unbalance can be higher. Because design and manufacturing techniques vary, the degree to which a given percent of voltage unbalance will cause current unbalance for energy-efficient motors varies a great deal. For some small energy-efficient motors (less than 20 horsepower), current unbalance can be as

high as nine times the voltage unbalance. On the other hand, some premium-efficiency motors may have about the same current unbalance for a given percent of voltage unbalance as a standard-efficiency motor. Figure 3-1 shows such a case for a 50-horsepower standard-efficiency and premium-efficiency motor.



**Figure 3-1. Effect of Voltage Unbalance for a 50-Horsepower Standard- and Premium-Efficiency Motor**

However, because energy-efficient motors have lower losses than standard-efficiency motors, they do not run as hot during a voltage unbalance, as shown in Figure 3-2. For a Design-E motor, the mitigating effect of lower stator and rotor resistance may be even more significant. Thus, although the current unbalance for an energy-efficient motor may be more, the temperature rise, which is the main detrimental effect of voltage unbalance, will be less for energy-efficient motors than for standard-efficiency motors.

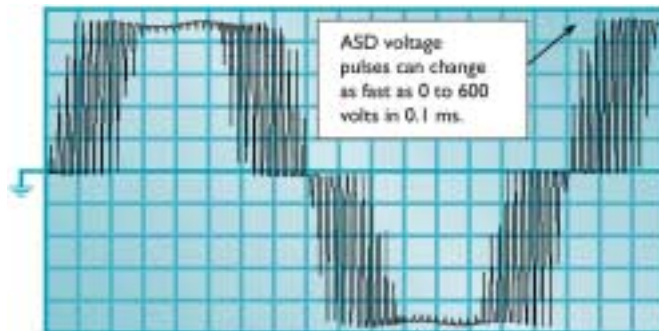


**Figure 3-2. Effect of Voltage Unbalance on Temperature Rise for a 50-Horsepower Standard- and Premium-Efficiency Motor**

## 3.2 Effect of Adjustable-Speed Drives on Motors

Advances in semiconductor devices have made adjustable-speed drives (ASDs) more affordable and thus more prevalent in industrial processes. To drive small- and medium-sized induction motors, most ASDs use pulse-width-modulation (PWM) inverters with switching frequencies

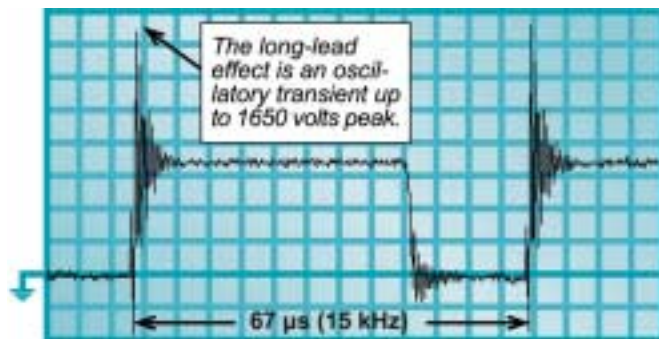
from 2 kHz to 20 kHz. As shown in Figure 3-3, the waveform of the inverter output voltage is composed of step-like functions, which are in effect voltage pulses with extremely quick changes in voltage magnitude (as fast as from 0 to 600 volts in 0.1  $\mu$ s).



**Figure 3-3. Output Voltage Waveform of a Pulse-Width-Modulation (PWM) Inverter**

### **3.2.1 Long-Lead Effect**

In many industrial applications, an ASD and the motor it drives are separated by tens or even hundreds of feet, which requires long cables, called motor leads, to connect the two together. Fast-changing PWM voltage pulses can interact with the distributed inductance and capacitance of the motor leads, which can result in an amplified peak voltage as high as 1600 volts at the motor terminals. This phenomenon, known as the long-lead effect, can stress and consequently degrade the insulation around the stator windings of the motor. The magnitude of peak voltage at the motor terminals depends upon the characteristics of the motor leads and the surge impedance of the motor. The smaller the motor and the longer the leads, the greater the peak voltage. Figure 3-4 shows an example of the resulting oscillatory transient known as the long-lead effect.

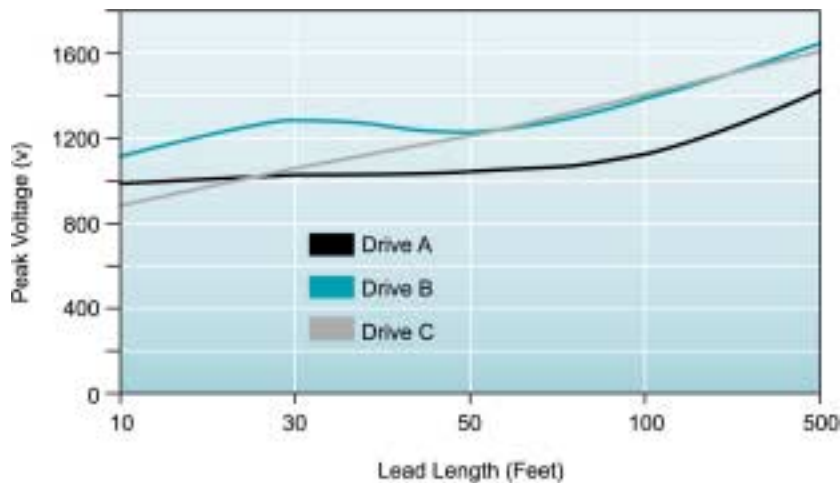


**Figure 3-4. Oscillatory Transient at the Motor Terminal Due to PWM Inverter Operation and Long Leads**

According to the standards IEEE 117-1974 and ANSI C50.21-1976, 480-V three-phase motors manufactured in the U.S. must withstand 600 AC volts (RMS) at 60 Hz. However, these standards do not apply to repetitive voltage transients. Therefore, there is no way to predict whether the voltage pulses produced by a PWM ASD will cause insulation damage. Many motor manufacturers voluntarily design the winding insulation of their motors to withstand voltages much greater than the IEEE and ANSI standards require, thus the hundreds of thousands of

ASD-driven motors operating without insulation damage. Still, some motors have winding insulation that cannot withstand the fast voltage pulses of a PWM ASD and the long-lead effect.

The most obvious symptom of the long-lead effect is the premature failure of a motor caused by degraded insulation. Damage to the insulation of the stator windings can progress gradually over a period of days or even months. The amplitude of voltage pulses, which stress the insulation, can be correlated to the length of the cable between the drive and the motor. As cable length is increased, the peak overvoltage at the motor terminals increases. Tests conducted with 5-Hp inverter-motor sets show that even for 10 feet of cable, the peak voltage at the motor terminal can be as high as 1100V, as shown in Figure 3-5.



**Figure 3-5. Peak Voltage at Motor Terminals as a Function of Lead Length**

One rule of thumb commonly used is that 50 feet is the critical cable length beyond which the chance of voltage doubling increases. However, with the new generation of PWM inverters—which feature IGBT (insulated gate bipolar transistor) switches—this rule of thumb no longer applies.

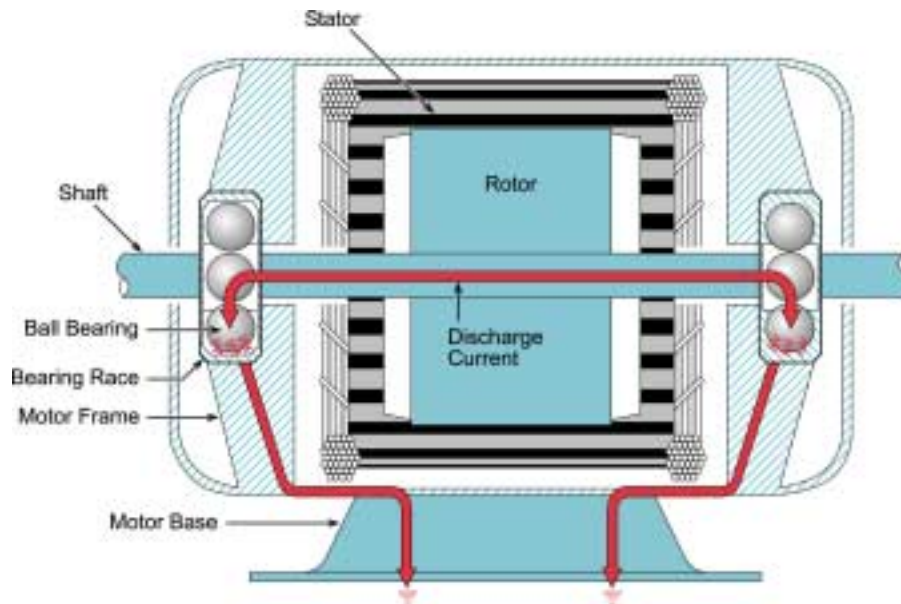
### **3.2.2 Premature Motor Bearing Failure**

Another problem associated with motors controlled by ASDs is bearing fluting. This problem was first noticed in light shaft-load applications such as in clean rooms and HVAC installations. However, problems have recently been reported from other industrial applications such as in paper mills. Understanding why the bearing is failing is as important as knowing when the bearing is going to fail. In most cases, bearing failures are catastrophic or occur just a couple of months after inverter installation. This does not mean that in other applications this condition does not exist. Most likely, the damage to the bearing happens over a period of time and is often attributed to other causes, resulting in premature bearing replacement.

The root cause of premature bearing failure in inverter-motor applications is electrical discharge machining (EDM) due to capacitively coupled shaft-to-ground voltage build-up. EDM, or fluting as it is more commonly called, is the passage of electrical current through the bearing.



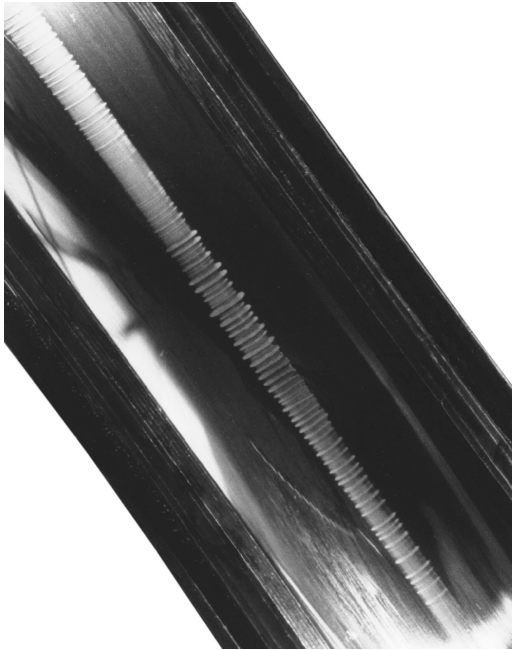
Historically, bearing fluting has been mainly attributed to circulating bearing current as shown in Figure 3-6.



**Figure 3-6. Electromagnetic-Induced Circulating Current**

The main reason for this circulating current is magnetic asymmetries in the construction of motors. The traditional approach for mitigating circulating bearing current is to break the path of the bearing current by insulating the non-drive end of the motor shaft.

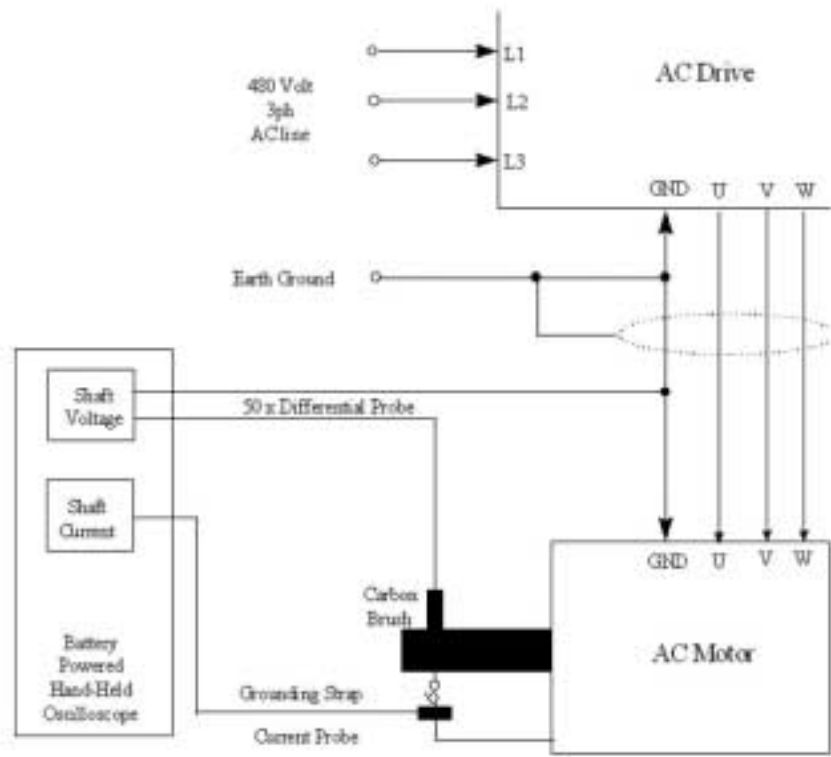
However, in PWM inverter applications, the shaft-to-ground voltage that results in bearing current is due to electrostatic coupling rather than electromagnetic induction, and breaking the current path does not mitigate this problem. The high rate of rise of PWM output voltage results in electrostatically induced shaft-to-ground voltage. The main coupling mechanism of this voltage is the stray stator-to-rotor capacitance, which acts as a low-impedance path for the fast-rising voltage pulses (typically less than 100 nanoseconds). The bearing lubrication acts as an insulator, allowing the voltage potential on the shaft to build up until it is greater than the breakdown level of the lubricant film or until metal-to-metal contact occurs. This typically causes current discharge similar to electrical arcing, which may cause metal to be removed from the bearing inner race over a period of time and cause bearing fluting, which has the appearance of being machined. On motors with a tachometer directly connected, the tachometer bearings are damaged first because the smaller bearings offer the least resistance to ground. Due to the electrostatic nature of this phenomenon, even if bearings are insulated, any ground path offered by gears, couplings, seals, and so on can also be damaged. As shown in Figure 3-7, fluting has a distinctive appearance of machining.



**Figure 3-7. Bearing Outer Race with Fluting Caused by Electrical Discharge Machining (EDM)**

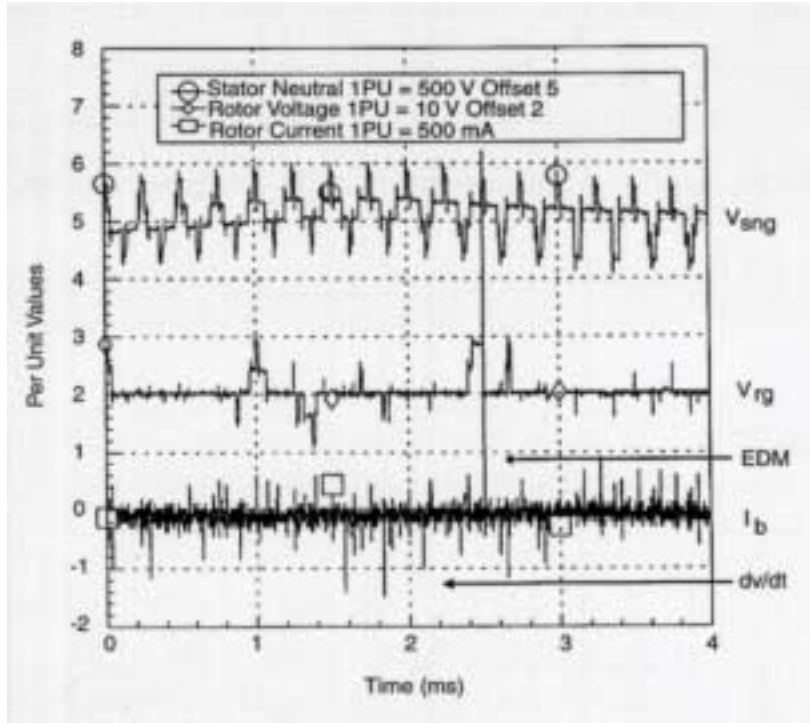
One of the obvious outcomes of fluting is the increase in noise level of the machine during normal operation. In addition to the noise level, an increase in temperature level can also be an indicator of a bearing problem. These signs typically indicate the possibility of a problem but do not provide any clues whether it is due to EDM. Visual recognition is one of the most effective ways to determine whether EDM is the root cause of the bearing failure. In many cases, the problems remain undiagnosed because the failed bearing is never inspected to identify the very clear sign of fluting due to EDM. Motors with bad bearings are typically sent to motor shops, where the bearings are changed without performing any failure analysis.

For years, electrical maintenance personnel have been limited to troubleshooting motors with no more than a multimeter for measuring voltage and resistance and a megaohmmeter for measuring resistance to ground. Unfortunately, these instruments do not provide enough information to properly diagnose EDM problems in inverter-driven motors. The required measurement instrument is a hand-held oscilloscope with a bandwidth sufficient to measure pulses with 100-nanosecond rise times. Many commercially available scopes at relatively low prices ( $\approx$  \$1000) will fulfill this requirement. Figure 3-8 shows the setup for the test fixture required to perform such an analysis.



**Figure 3-8. Test Setup for Measuring Shaft-to-Ground Voltage and Discharge Current**

The main pick-up element is a shaft-riding brush, wire whisker, or other conductive pick-up, placed directly on the rotating shaft in order to measure the actual level of voltage and current. A review of existing references shows that there is no consensus as to the level of shaft-to-ground voltage that may indicate a problem. The only positive way to identify these problems is to measure the current directly through the arrangement shown in Figure 3-8. Figure 3-9 shows the difference in the EDM current and the normal  $dv/dt$  current that is present due to the capacitive current induced by the rate of change of the voltage on the inverter output. The EDM current is characterized by a very narrow pulse ( $\approx 100$  nanoseconds), whose amplitude is an order of magnitude higher than the normal  $dv/dt$  current.



**Figure 3-9. Shaft-to-Ground Voltage and EDM Current**

An effective way to interpret the shaft-to-ground voltage readings, which are relatively easier to measure, is to trend this data. Changes that deviate from the mean by greater than 3 of the standard deviation should be considered excessive, and the situation should be investigated to determine the cause of the deviation. Changes of this magnitude can be an indication of the start or worsening of a problem that can cause unscheduled downtime associated with high maintenance cost.

# 4

## GROUNDING ISSUES

The primary function of grounding is to provide safety for equipment and personnel. However, grounding also provides a path for lightning and surge mitigation and establishes an equipotential or zero-voltage reference point for the electrical system. In addition, a grounding system is designed to ensure the proper and efficient operation of sensitive electronic equipment. Performance grounding must be accomplished without conflict with the safety requirements of the National Electric Code.

### 4.1 Requirements of the National Electric Code

The purpose of the National Electric Code (NEC) is to ensure that grounding is designed and installed to provide practical safeguarding of persons and property from hazards arising from the use of electricity. During a fault condition in electrical and electronic equipment, grounding provides a return path for fault current to trip the assigned circuit breaker. Grounding is addressed in Article 250 of the NEC. This article was completely rewritten in the 1999 revision to the NEC. Article 250-50 requires that at each building or structure served, metal underground water pipes, supplemental electrodes, metal frames of the building, and concrete-encased electrodes (rebar) be bonded together to form the grounding electrode system. This requirement is illustrated in Figure 4-1.

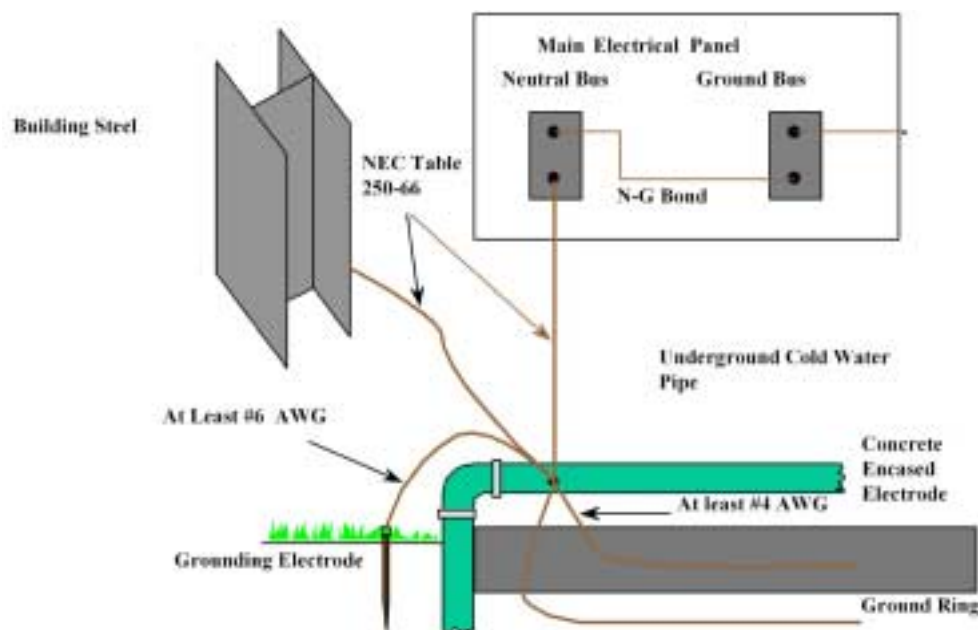


Figure 4-1. Example of Grounding Electrode System

This grounding practice establishes a zero-voltage reference for an electrical power distribution system, as well as provides protection to the electrical system and equipment from superimposed voltages from lightning and contact with higher voltage systems. It also prevents a buildup of potentially dangerous static charges in a building. Some electronic equipment does not work properly with an ineffective power system ground.

Article 250-110 of the NEC requires that exposed non-current-carrying metal parts or fixed equipment likely to become energized be grounded. An equipment grounding conductor must be run with the circuit conductors to this equipment. Article 250-118 permits the metal conduit to serve as this grounding conductor, but for a more reliable grounding system, a separate grounding conductor sized per Table 250-122 should be run. An example of this grounding conductor is shown in Figure 4-2.

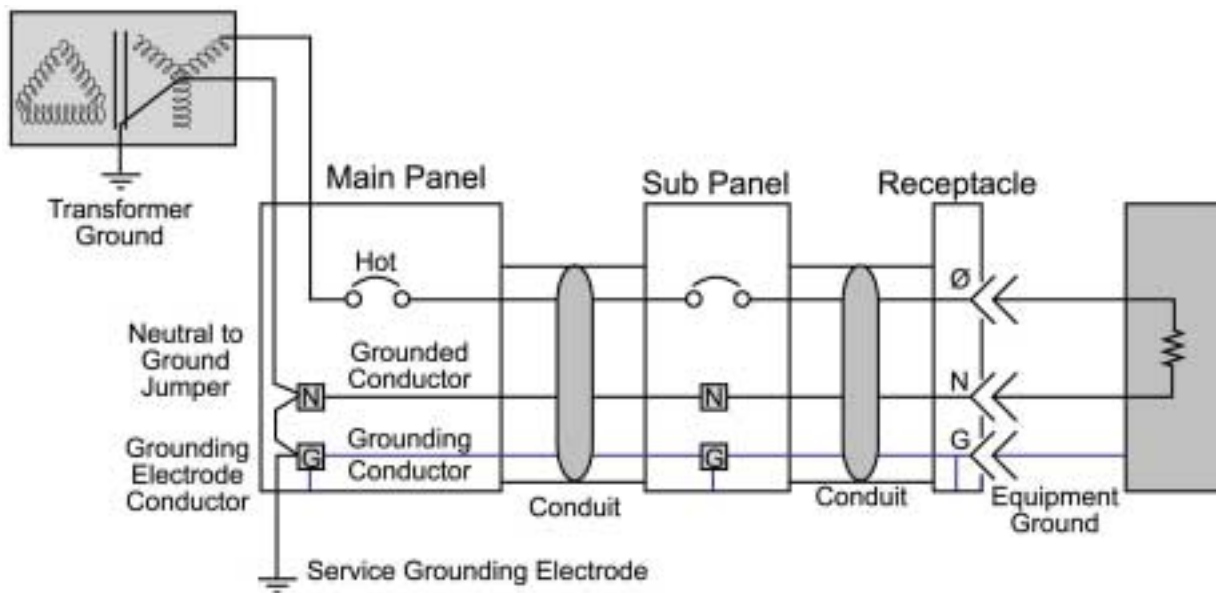
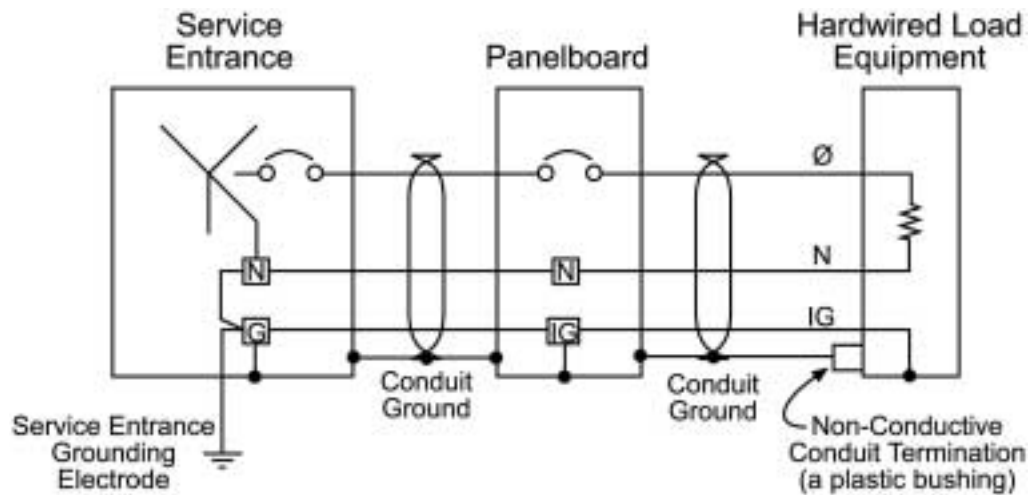


Figure 4-2. Example of Grounding Conductor

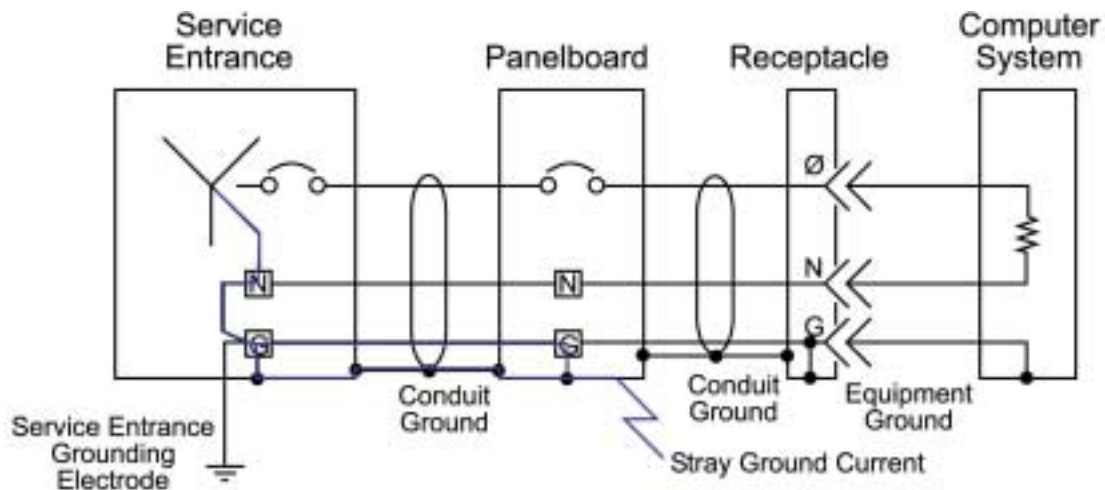
## 4.2 Isolated Grounds

Article 250-96 (b) of the NEC permits the use of an isolated grounding circuit when required for the reduction of electrical noise on the grounding circuit. The enclosure supplied by an isolated ground circuit will be isolated from the raceway supplying the equipment by a non-metallic raceway fitting located at the point of attachment of the raceway to the equipment. In addition, a grounding conductor will run from the equipment through panelboards without connection to the panelboard grounding terminal to terminate where the system ground is established. An example of an isolated ground system is shown in Figure 4-3.



**Figure 4-3. Example of Isolated Ground Circuit**

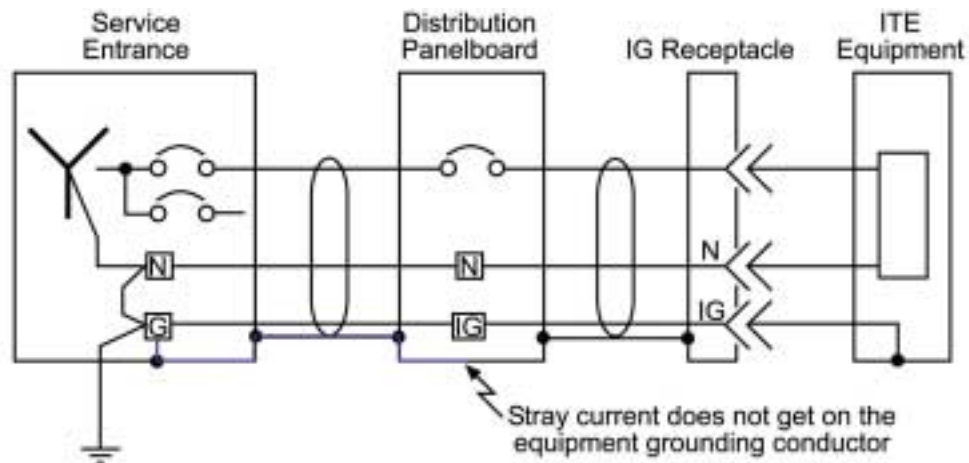
An isolated ground should only be used when there are concerns about stray currents. As shown in Figure 4-4, stray currents can develop on traditional ground circuits, which can create electromagnetic interference that affects the operation of equipment.



**Figure 4-4. Stray Ground Currents with Traditional Grounding**

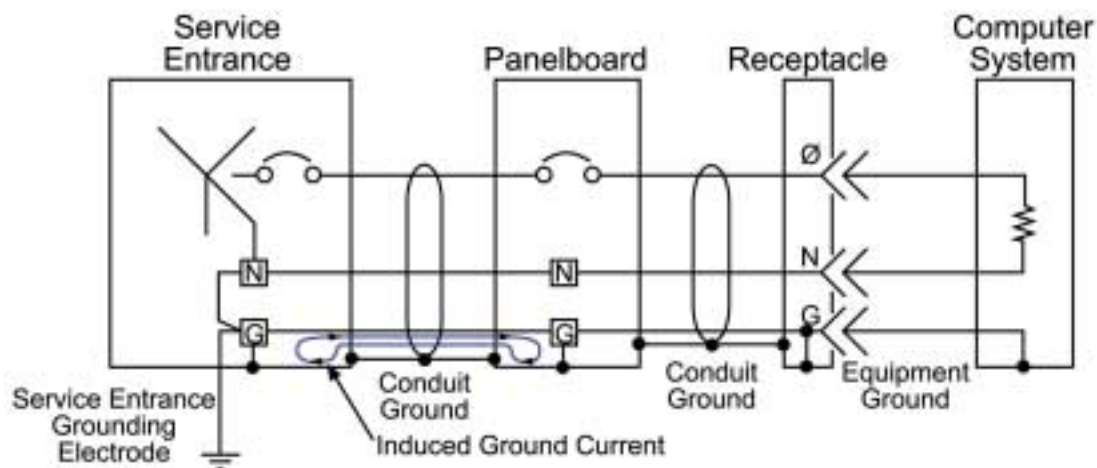
As seen in Figure 4-5, the use of an isolated grounding system will eliminate the problems associated with stray currents.





**Figure 4-5. Isolated Ground Eliminates Stray Currents**

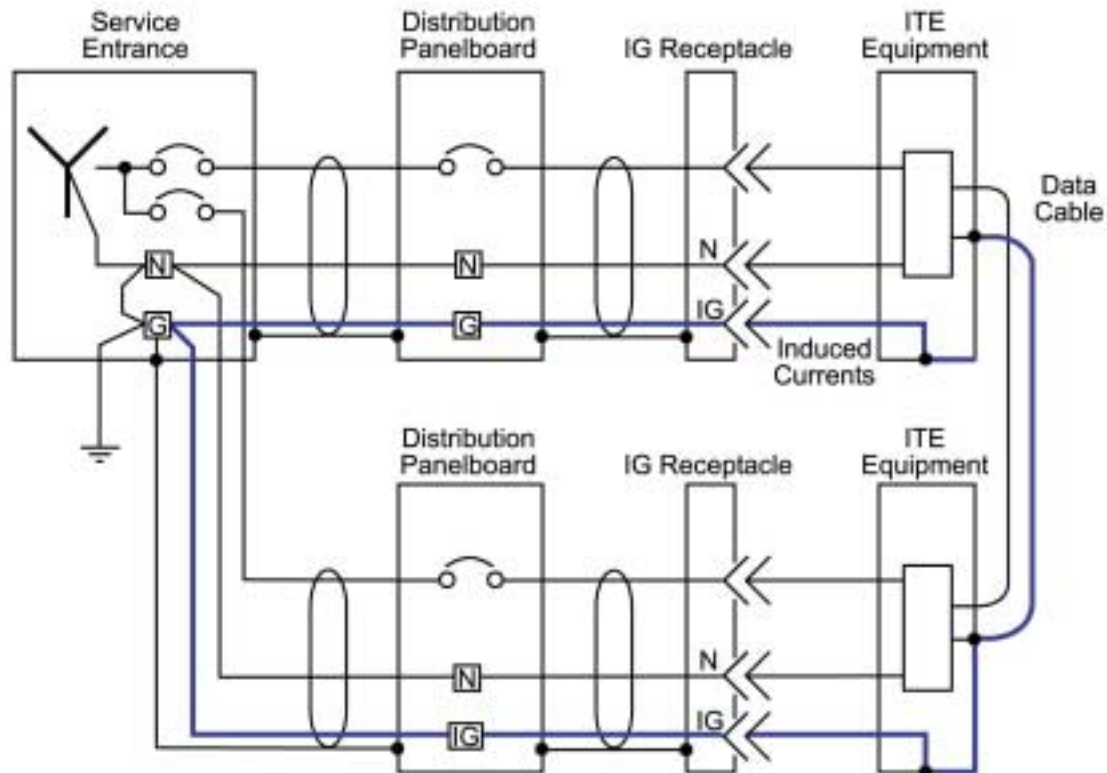
Isolated grounds should only be used where stray currents are a concern because this type of configuration can lead to induced currents. This can occur due to the long length of ground cable running concurrently with the phase conductors. With the traditional grounding system, the relatively short runs of cable will lead to small loops of induced ground current. An example of this is shown in Figure 4-6.



**Figure 4-6. Induced Ground Current in Traditional Grounding System**

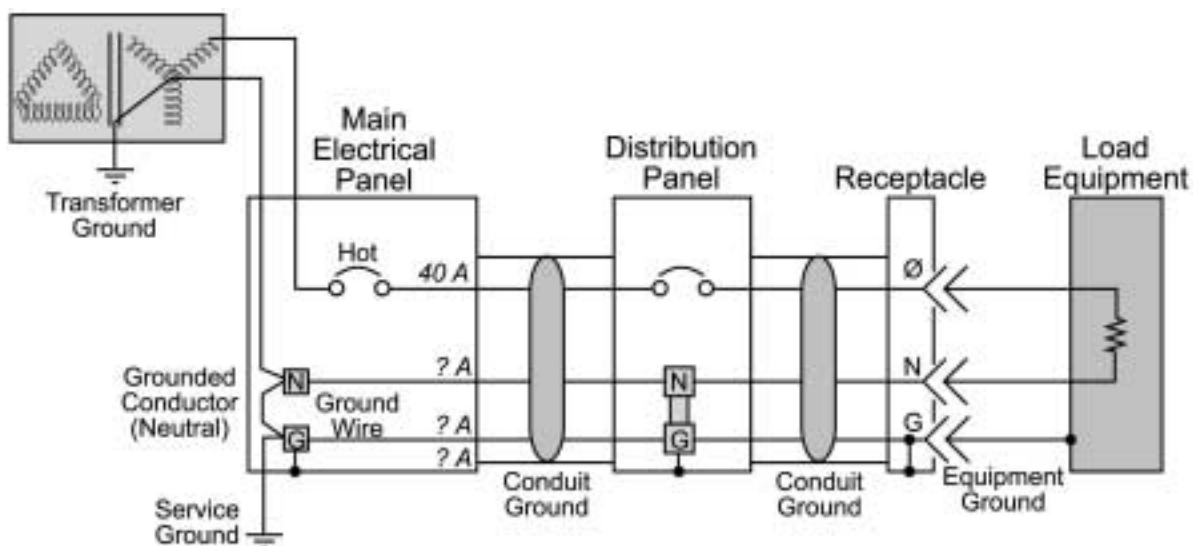
With an isolated grounding scheme, the effect of induced ground current can impact operation of the load. Figure 4-7 shows an example of how induced ground currents can be created in an isolated ground circuit.





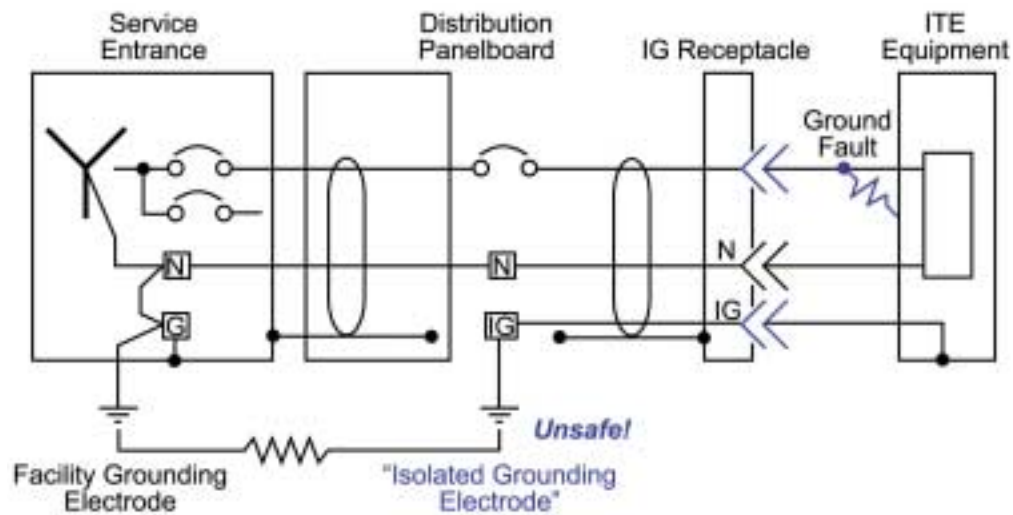
**Figure 4-7. Induced Ground Current in Isolated Ground Circuit**

Two of the most common grounding errors that are seen in industrial grounding systems are incorrect neutral-to-ground bonds and incorrect wiring of isolated ground circuits. A common error in neutral-to-ground bonding is using multiple neutral-to-ground bonds. It is not unusual for some systems to be bonded at the main distribution panel as well as at downstream panels. An example of this practice is shown in Figure 4-8.



**Figure 4-8. Improper Multiple Neutral-to-Ground Bonding**

Another common error is incorrectly wiring isolated grounding circuits. Many times, an electrician will mistakenly believe that driving another ground electrode will satisfy the requirements of isolated grounds. Correctly wired isolated ground circuits will have a ground wire that runs uninterrupted to the ground source. An example of the incorrect wiring of isolated grounding is shown in Figure 4-9. This wiring method is unsafe because the configuration uses earth to connect the isolated ground to the power ground.



**Figure 4-9. Incorrectly Wired Isolated Ground**

# 5

## ELECTROMAGNETIC INTERFERENCE INTERACTIONS

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Electromagnetic interference (EMI) is any natural or man-made electrical or electromagnetic energy that results in unintentional and undesirable equipment responses. Electromagnetic energy travels in the form of emissions, either conducted or radiated.

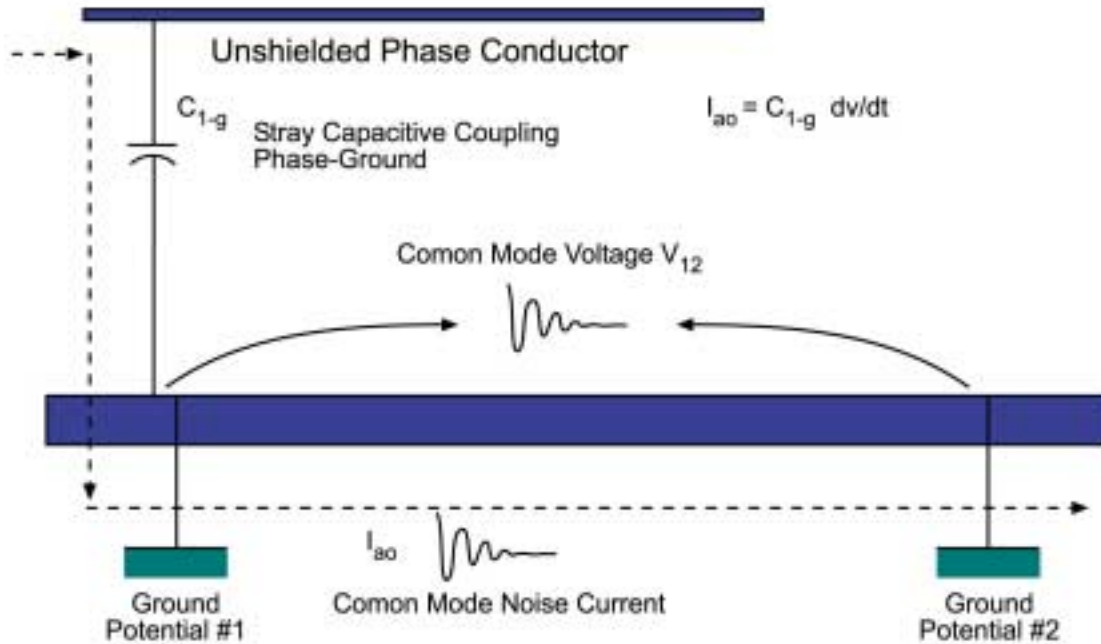
Conducted emissions are generated inside electrical or electronic equipment and may be transmitted outward through the equipment's data input or output lines, its control leads, or its power conductors. Conducted emissions may cause an EMI problem between equipment that generates useful emissions and other equipment with low immunity to those same emissions.

Radiated emissions are radio-frequency electromagnetic energy that travels through the air. Radiated emissions are also generated by electrical or electronic equipment and may be emitted from poorly shielded or unshielded power and data cables, leaky equipment apertures, inadequately shielded equipment housings, or normally operating equipment antennae.

Whether conducted or radiated, emissions include three properties: amplitude, frequency, and waveform. EMI can occur in equipment with low immunity to emissions when any or all of these properties vary from normal—for example, emissions that are too high in amplitude, too low or too high in frequency, or whose waveforms are distorted. EMI can also occur when these properties are within normal operating parameters, usually resulting from an equipment's low immunity to emissions.

### 5.1 Causes of Electromagnetic Interference

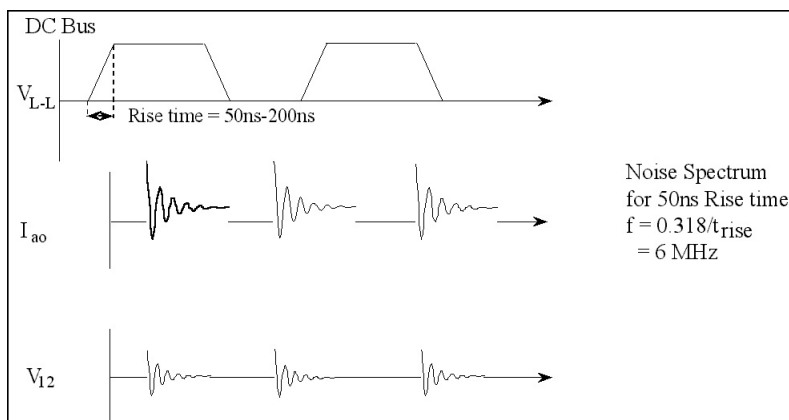
EMI is generally common-mode noise, which is induced onto a signal with respect to a reference ground. The noise is coupled to ground from the power cables through the capacitance between the power cable and ground. Figure 5-1 demonstrates this principle.



**Figure 5-1. Capacitive Coupling from Ground to Phase Conductor**

The capacitance between the cable and ground increases as the length of cable increases. Therefore, short lengths of motor cable (< 20 ft) have a low risk of common-mode noise. As the length of cable increases, the risk of common-mode noise increases and the need for EMI solutions rises.

As shown in Figure 5-2, the common-mode ground current ( $I_{ao}$ ) =  $C_{1-g} dv/dt$ . This characteristic of common-mode current makes the adjustable-speed drive a prime source of common-mode noise because of its abrupt voltage transitions on the drive output terminal. The conducted noise will be created as the individual pulses on the drive output couple with the ground conductor. Figure 5-3 demonstrates how the conducted noise tracks the drive output voltage and how this is also reflected into the voltage between points 1 and 2.



**Figure 5-2. Drive-Induced Common-Mode Current and Voltage**

Some common symptoms of EMI related problems are:

- Unexplained drive trips with no correlation with voltage disturbances.
- Malfunctions of barcode/vision systems, ultrasonic sensors, weighing and temperature sensors
- Intermittent data errors in drive-control interfaces such as encoder feedback, I/O, and 0-10-V analog out
- Interference with TV, AM radio, radio-controlled devices

Radiated emissions from many types of electronic equipment—including ASDs, lighting systems, broadcast communication equipment, and medical equipment—have been shown to cause electromagnetic interference with other types of sensitive electronic equipment. Figure 5-3 shows how radiated emissions propagated through the electromagnetic environment may interfere with microprocessor-based sensitive electronic medical equipment.

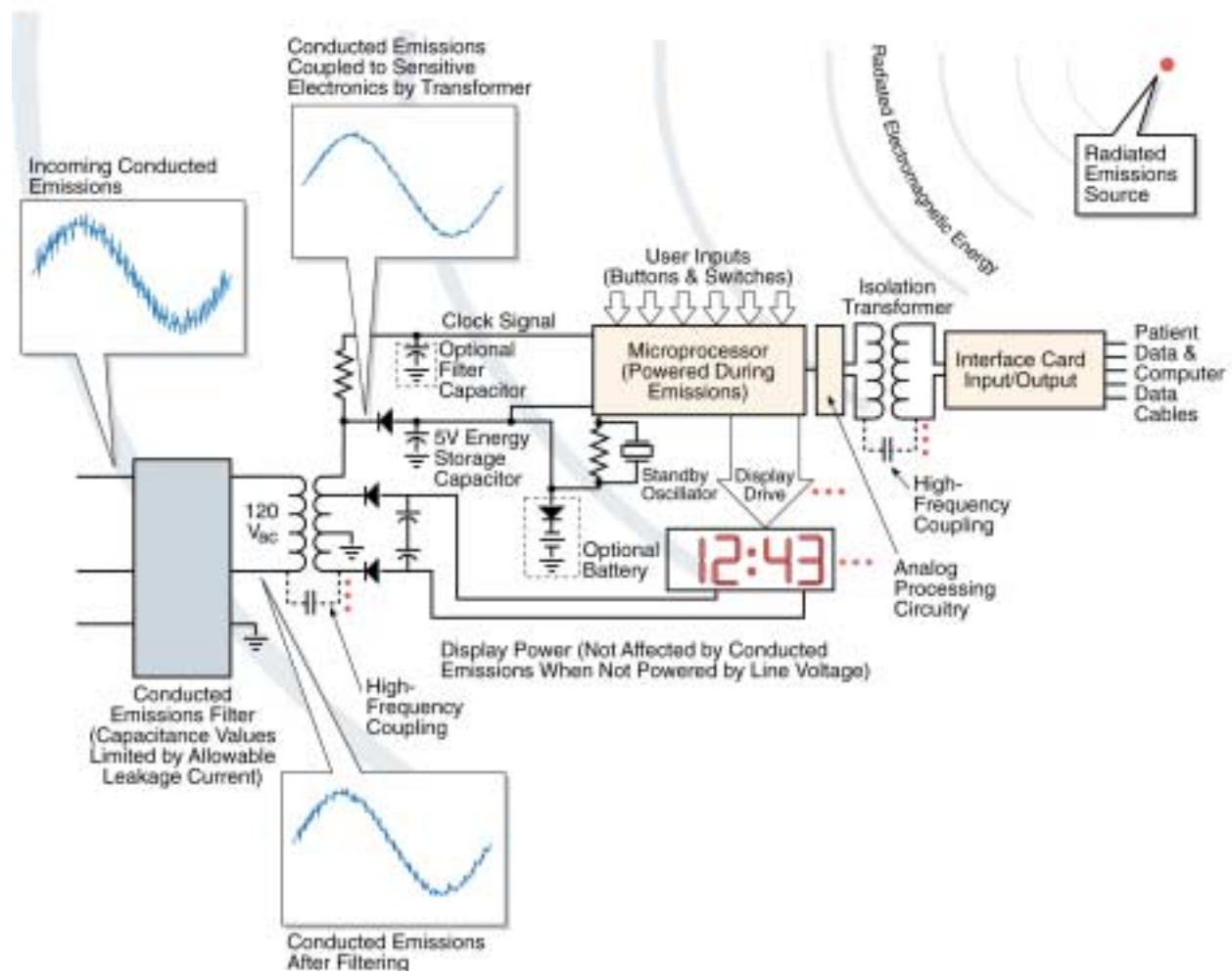


Figure 5-3. Example of Radiated Emissions Interfering with Equipment

Ungrounded shields or floating shields can act like an antenna to unwanted radiated emissions. Connectors usually contain several pieces and are used to mechanically secure a cable to a piece of equipment. In the case of a shielded cable, a cable connector also helps to electromagnetically connect the cable shield to the equipment enclosure. The pieces of a connector must fit together properly and securely to ensure the electromagnetic integrity of the connector. Particular attention must be paid to how the pieces fit together during connector installation. Improperly fitted or loose connector joints can cause electromagnetic leaks in the connector, which can allow unwanted radiated electromagnetic energy from the electromagnetic environment to penetrate the cable system.

# 6

## SOLUTIONS AND POWER-CONDITIONING EQUIPMENT

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The previous sections of this guidebook identified some of the electrical disturbances that occur on a power distribution system and how they can affect an industrial facility. The adverse effects of these disturbances can be mitigated by installing power-conditioning equipment or by utilizing different wiring or power-distribution methods. As with most system enhancements, the cost of the solution must be evaluated against the losses associated with the disturbance. This section will identify the most common solutions, when to apply them, and the approximate cost of applying them.

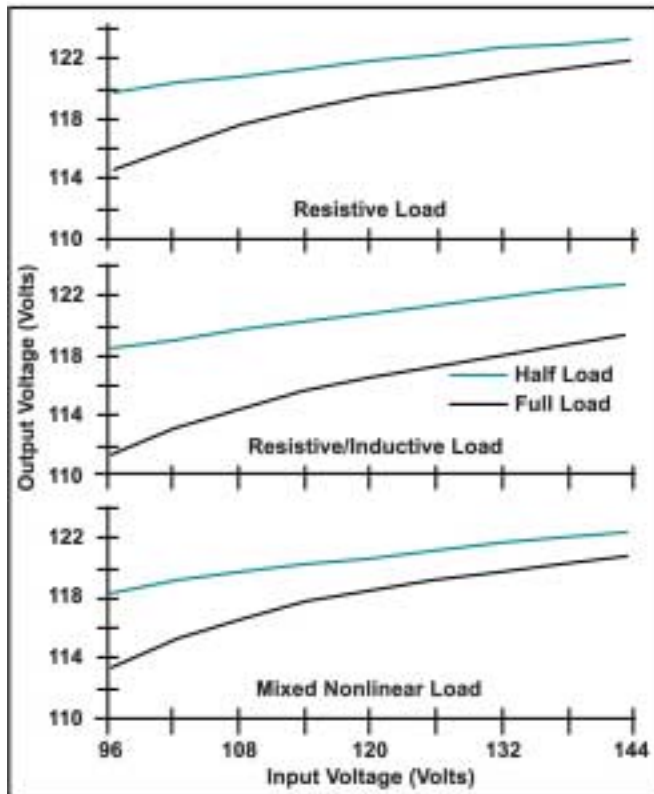
### 6.1 Solutions to Voltage Sags

#### *6.1.1 Solutions for Control Circuits*

##### 6.1.1.1 Ferroresonant Transformer

Most voltage-sag solutions can be handled by ferroresonant transformers. These power conditioners are also known as constant-voltage transformers (CVTs). CVTs are ideally suited for constant, low-power loads. Unlike conventional transformers, the CVT allows the core to become saturated with magnetic flux, which maintains a relatively constant output voltage during input voltage variations such as undervoltages, overvoltages, and harmonic distortion.

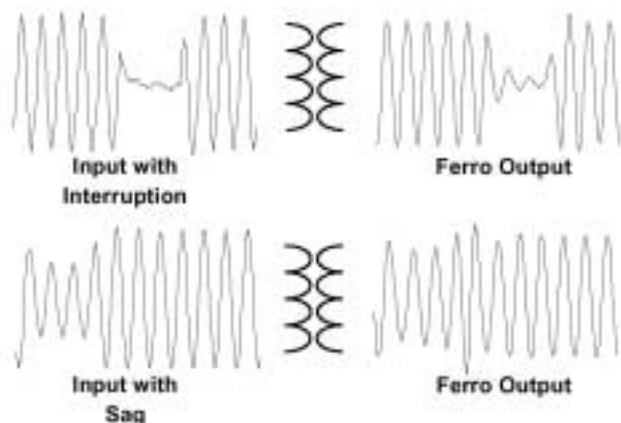
CVTs are usually 1:1, single-phase transformers used with 120-V control circuits or other small loads. For the best results, the CVT should be sized at least two times the load current. Figure 6-1 shows the typical output of a ferroresonant transformer with respect to transformer loading.



**Figure 6-1. Output Voltage Regulation of a 1000-VA Constant-Voltage Transformer (CVT)**

Another consideration when sizing a CVT is the load characteristic. A CVT must be sized for the maximum load. When the transformer is overloaded, the voltage will decrease and collapse to zero at approximately 150% of loading. Therefore, if the load profile includes an inrush current or a starting motor, the transformer must be sized for this transient load, not the steady-state load.

It must also be recognized that a CVT has no significant stored energy. Therefore, it is only applicable for protection against voltage sags, not interruptions. Figure 6-2 demonstrates the response of a CVT to both an interruption and a voltage sag.



**Figure 6-2. CVT Output Response to Input Variations**

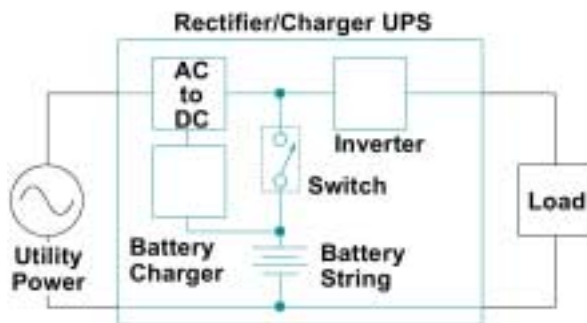


The cost of a CVT is relatively low compared to other power conditioners. It also has the advantage of low maintenance because there are no moving parts or batteries to maintain. The approximate material cost of a CVT is \$1000 per kVA.

#### 6.1.1.2 Uninterruptible Power Supply

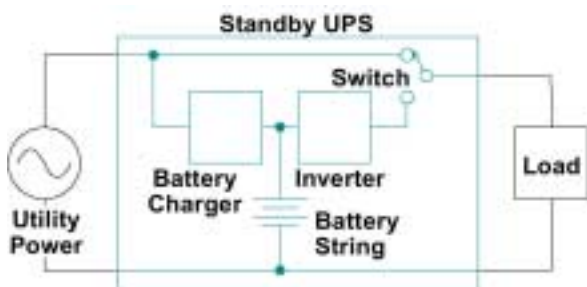
A UPS system is designed to provide uninterrupted power to the protected load, regardless of the conditions of the supply system. A UPS utilizes stored energy to provide power to the load when the normal power supply falls outside a predetermined voltage level. They are also characterized by the quality of the voltage and current waveforms on the input and the output. The three most common types of UPSs are the rectifier/charger, line-interactive, and standby.

A rectifier/charger UPS always feeds the load through the UPS. The incoming AC line is rectified into DC power, which charges the batteries. This DC power is then inverted back into AC power to feed the load. If the incoming AC power fails, the inverter is fed from the batteries and continues to supply the load. This type of UPS is typically the most expensive type, but provides a transition to battery power with no interruption. Figure 6-3 shows a typical schematic of a rectifier/charger UPS.



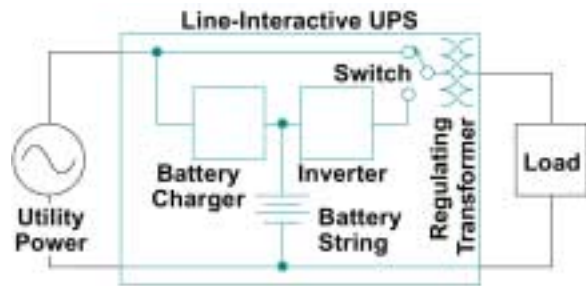
**Figure 6-3. Rectifier/Charger Uninterruptible Power Supply**

A standby UPS supplies power from the batteries only when the supply voltage falls outside the predetermined limits. During normal conditions, the batteries charge through the battery charger, but the inverter is not supplying power to the load. If the utility supply fails, the load transfers from the utility to the inverter. These units are the least costly UPS and provide adequate sag protection for most loads. Figure 6-4 shows a typical schematic of a standby UPS.



**Figure 6-4. Standby Uninterruptible Power Supply**

A line-interactive UPS is similar in configuration to a standby UPS, but utilizes a ferroresonant transformer after the transfer switch. This transformer will prevent the load from switching to the UPS until the supply voltage falls to a level that cannot be mitigated by the ferroresonant transformer. Figure 6-5 shows a typical schematic of a line-interactive UPS.

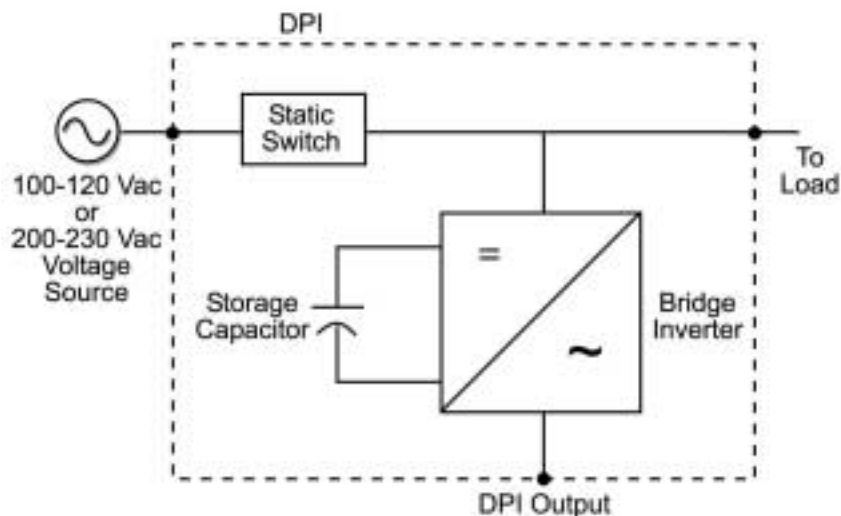


**Figure 6-5. Line-Interactive Uninterruptible Power Supply**

For additional information on UPSs, visit [www.liebert.com](http://www.liebert.com) , [www.apcc.com](http://www.apcc.com) , [www.bestpower.com](http://www.bestpower.com) , and [www.mgeups.com](http://www.mgeups.com).

#### 6.1.1.3 Dip-Proof Inverters

The dip-proof inverter (DPI) is a relatively new off-line device that is sized for the nominal load. The device continually rectifies incoming AC voltage to charge DC bus capacitors. When it detects a voltage sag that drops below an adjustable threshold, the line to the incoming power is opened and the DPI supplies a square-wave output to the load for about 1 to 3 seconds. The amount of time that the load will be supplied can be calculated based on the real power and the energy storage of the particular DPI. Figure 6-6 shows a schematic of a typical DPI.



**Figure 6-6. Dip-Proof Inverter**

Because a DPI does not have batteries, it is a low-maintenance item. The rated lifetime for the capacitors is twelve years. The DPI is also compact and lightweight when compared to either the

CVT or the UPS. Because the standard voltage setups for the units are 120 and 230 VAC, the purchaser must specify the nominal voltage if it is different in order for the factory to preset the DPI. Because the DPI output is a square wave, the equipment vendor should be consulted during the final design of the installation. The square-wave output has been found to be incompatible with only a handful of components. For additional information on DPIs, see [www.dipproof.com/html/research.htm](http://www.dipproof.com/html/research.htm).

### **6.1.2 Solutions for Adjustable-Speed Drives**

Reprogramming an ASD's response to a voltage sag may be an option if the process requirements will allow deviations in the speed and torque of the motor. If the application does not require an operator to restart the process, the ASD may be able to be reprogrammed to provide a non-synchronous time-delay restart. Once the motor coasts down to zero speed, this feature will restart the motor after a user-defined time delay.

Another reprogramming feature is a non-synchronous ride-through with flying restart. When the DC bus drops to the undervoltage trip point, the drive stops firing the IGBTs of the inverter. In doing so, the drive loses control of the motor and the load. The motor and load coast during the time that the DC bus voltage remains at the undervoltage trip point. The torque of the motor drops to zero, and the speed reduces. When the DC bus voltage rises above the trip point, the drive performs a flying restart to determine the speed of the motor and accelerates the system back to the original operating point. The speed change is determined by the duration of the sag, the system inertia, and the load torque. Processes that can tolerate significant speed and torque deviations are suitable for non-synchronous ride-through with flying restart.

The flying restart algorithms are not always the same between different drive manufacturers. Some manufacturers will have more accurate algorithms than others. Thus, a process may see different speed and torque changes between drives with flying restart algorithms from different manufacturers. Flying restart often produces significant current and torque transients on the motor. Therefore, process engineers should consult drive and process machine manufacturers before enabling flying restart.

Another programming option is to reduce the DC bus undervoltage trip point. Some processes require precise speed and torque regulation. Because the torque and speed vary when the DC bus reaches the undervoltage trip point, some drive manufacturers offer software revisions for existing drive applications that allow users of AC drives to lower the DC bus undervoltage trip point. By lowering the trip point, drives and processes can ride through longer and deeper voltage sags without interrupting production. Often, the software revisions are not part of the standard drive control software and must be requested from the manufacturer. The drawback to this approach is that rectifiers and fuses may be damaged due to high inrush current and overcurrent conditions. The current increases as the DC bus undervoltage trip point decreases. These conditions should be considered when lowering the undervoltage trip point.

### **6.1.3 Large-Scale Solutions**

#### **6.1.3.1 Large-Scale Written Pole Motor Generator**

The written pole motor generator provides such benefits as low inrush current on start and synchronous motor speed. This unit is available in sizes up to 250 kW and can supply power for up to 15 seconds during an interruption of voltage. Additional information on this type of device can be found at [www.precisepwr.com/protection.htm](http://www.precisepwr.com/protection.htm).

#### **6.1.3.2 Superconducting Magnetic Energy Storage (SMES)**

A SMES consists of a superconducting coil that carries megawatt levels of current at practically zero electrical resistance. A power electronic converter is used to divert the current into a capacitor if energy is to be extracted from the SMES. A SMES unit is designed to protect the whole of an industrial facility. The units can produce from 300 kW to several megawatts for several seconds. Additional information on this device can be found at [www.igc.com](http://www.igc.com) or at [www.amsuper.com](http://www.amsuper.com).

#### **6.1.3.3 PQ 2000**

The PQ 2000 is a high-capacity standby power system. The system topology is similar to that of a standby UPS in that energy from batteries supplies power to the load when the normal source voltage falls outside predetermined limits. This unit differs from the traditional UPS in that it is designed to supply power to large loads for a short duration of time. The units are rated as high as 2 MVA for a minimum of 15 seconds. The units can be provided to supply both low-voltage and medium-voltage loads. They are available from Omnion ([www.omnion.com](http://www.omnion.com)). A similar unit known as the “Pure Wave” is available from S&C ([www.sandc.com/ped/pwproducts.htm](http://www.sandc.com/ped/pwproducts.htm)).

## **6.2 Solutions to Utility Transients**

### **6.2.1 Solutions to Capacitor-Switching Transients**

#### **6.2.1.1 Adjustable-Speed Drives**

Using reactors at the input of an ASD or connected to its DC link is the most cost effective way to minimize the effect of capacitor-switching transients on ASDs. In the early days of drives, magnetic components such as front-end reactors and/or DC-link reactors were standard on ASDs, but with the advancement of semiconductor devices (and as the result of cost-cutting measures), manufacturers have decided not to use reactors—especially for smaller drives (< 50 HP). Instead, they make reactors an optional item, placing the burden of acquiring them on the end user.

Reactors provide two main functions that help to minimize the effect of capacitor-switching transients. First, the reactor impedance, expressed as a percentage of the base rating of the drive,

provides a voltage drop that reduces the DC bus voltage, thereby providing a greater margin for overvoltage trip. Second, reactors limit the magnitude and the rate of the surge current charging the capacitor. The required reactor size is a function of the transient magnitude, impedance of the source, and drive trip point. Usually a 3% reactor is sufficient. It must be noted, however, that drives with SCR front-ends such as DC drives and current source drives might already have an isolation transformer installed. In such a case, adding an additional reactor would significantly reduce the available short-circuit current and would magnify the notching created by such drives on the load side of the reactor. In some cases, where the capacitor-switching transient may be magnified due to local resonance with the low-voltage capacitor, the peak overvoltage could be higher than 2 p.u. For such cases, a 5% reactor might be needed.

The effect of capacitor-switching transients can also be relieved by modifications inside the drive. One method that can be used to provide a built-in solution would be to provide a time delay in the trip command of the drive for momentary overvoltages. Obviously, no equipment can function if the steady-state voltage increases to 800V. However, for momentary transients such as capacitor-switching transients, the duration of the peak voltage is in the order of a couple of milliseconds. If the internal components inside the drive are able to withstand a short-duration overvoltage, then programming a time delay would eliminate most of the problems of nuisance tripping of drives due to capacitor-switching transients. At a minimum, manufacturers should provide information regarding the sensitivity of the transient overvoltage trip so that the end user or the system integrator can take proper measures before installing drives to run critical processes.

### 6.2.1.2 Utility-Side Solutions

There are several options that are available on the utility side to minimize the transient overvoltage resulting from capacitor switching. The problem with all of the options are that the installed cost ranges anywhere from \$20,000 to \$100,000, depending upon the voltage levels and the size of the capacitor banks. Unless the customer involved is willing to share the extra cost for implementing these solutions, it is not equitable for all of the other customers to pay for these options in their rate base. Some possible utility-side solutions are:

- Switching capacitor banks in incremental steps by installing individual breakers for each step.
- Installing line reactors or pre-insertion resistors in series with the capacitor bank.
- Installing synchronous close-switching devices on the capacitor banks.

## 6.3 Solutions to Surges

Utility voltage surges caused by lightning or switching can be mitigated by surge-suppression devices. Surge-suppression devices protect equipment by diverting the energy to ground when the voltage exceeds the breakdown voltage of the device. For example, lightning arrestors can be placed at the level of the power distribution substation. Lightning arrestors are usually spark-gap devices. Normally behaving as insulators, it will arc over internally and become a short circuit at or above its breakdown voltage. Then, the current through it drops to zero, usually at the next AC zero crossing.

Because not all surges are generated on the utility side of the plant, it is advisable to provide additional protection in the power distribution system. The most common clamping element used is the metal-oxide varistor, or MOV. The resistance across an MOV decreases as the voltage across it increases. When subjected to large voltage surges, the resistance drops so that the energy is diverted away from the load to neutral or ground. Transient voltage surge suppressors (TVSSs) can be applied as plug-in loads, hardwired applications on branch circuits, and panelboard units. For maximum protection, these should be applied as staged protection. This method requires that a unit with high current capacity and moderate clamping level be applied at the service entrance to divert most of the current. A unit with medium current capacity and medium clamping level would be applied at panelboards, and a unit with low current capacity and low clamping level would be applied on branch circuits.

To achieve maximum performance, a TVSS must be installed with short lead lengths and a very good ground connection. When data or communication circuits are also used on a piece of protected equipment, it is important that communication circuits also be protected from surges. A surge reference equalizer can be used for these pieces of equipment. A surge reference equalizer references the ground of the data line to the ground of the power line to prevent ground offset voltages.

### **6.4 Solutions to Harmonic Problems**

The affect of harmonic currents on facility devices can be reduced in several ways. One method is to add harmonic filters to divert the harmonic current from facility equipment. A second method is to add reactors or isolation transformers on the feeders connected to harmonic-producing loads. A third method is to isolate the harmonic loads from other sensitive equipment so that the harmonic level at the sensitive loads is lower due to the system impedance between the harmonic source and the sensitive loads.

Harmonic-current filters prevent the harmonic currents drawn by facility non-sinusoidal loads from being fed back into the power system. Filters can be applied at substations to prevent the harmonic current from being fed back into the utility, or they can be installed parallel to individual loads to prevent the currents from affecting the plant power distribution system. Harmonic filters also provide the benefit of increasing the power factor of the facility due to the capacitance present in the filter.

Isolation transformers and line reactors can also be used to reduce the effects of harmonics on the power distribution system. The most common application of line reactors are with ASDs. As mentioned previously, line reactors will decrease the likelihood of ASDs tripping on overvoltage when exposed to a capacitor-switching transient. In addition to this benefit, the reactance of this device will attenuate the harmonics produced by an ASD.

Isolation transformers also provide reactance to attenuate harmonics in a manner similar to line reactors. In addition to providing reactance to the circuit, most isolation transformers will eliminate third harmonics. Isolation transformers usually include a delta winding. One characteristic of a transformer with a delta winding is that zero-sequence currents cannot pass through the winding. Zero-sequence currents include ground currents as well as third-harmonic

currents, so the application of this device isolates the feeder from third harmonics and ground faults produced at the load.

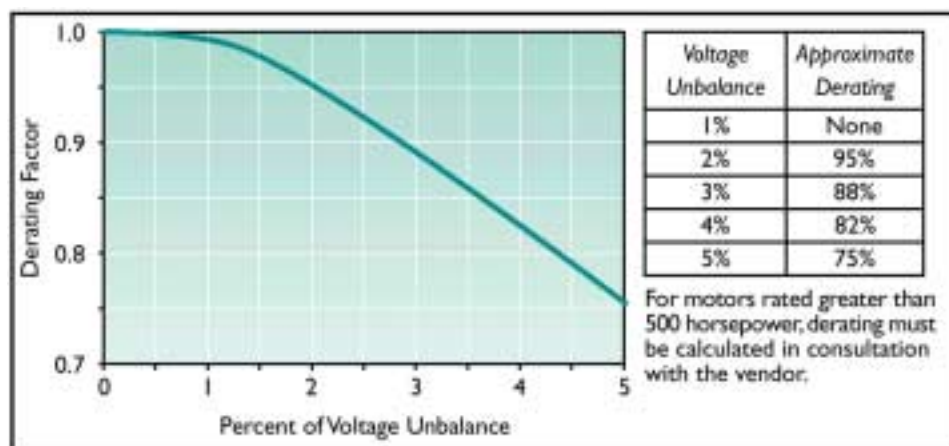
## 6.5 Solutions to Motor Issues

### 6.5.1 Voltage Unbalance

The most effective way to solve the problems of motors overheating due to voltage unbalance is to eliminate the unbalance. The unbalance can be caused by unbalanced single-phase loads, faulty connections, or malfunctioning voltage regulators. Each of these possibilities should be explored to eliminate the source of the unbalance. If the voltage unbalance cannot be eliminated, the motor must be derated to ensure long life.

NEMA Standard *MG 1-14.35* recommends derating an induction motor when the voltage unbalance exceeds one percent and recommends not operating a motor at all when the voltage unbalance exceeds five percent. If the motor is not equipped with an embedded temperature detector or if incorporating the detector into a protection scheme is not feasible, then the motor user should consult with the motor manufacturer to determine the maximum level of current unbalance for all loading conditions.

For example, the effect of a 10-percent current unbalance on a motor that is fully loaded is greater than the effect on the same motor if the motor is loaded at only 50 percent. Essentially, the operation of a motor during unbalanced-voltage conditions requires the motor to be derated. For standard motors, NEMA provides guidance for derating. For voltage unbalances between one and five percent, NEMA *MG-1-1993* suggests derating motors according to the graph shown in Figure 6-7. NEMA has not yet established a derating graph for energy-efficient motors. However, because energy-efficient motors have lower losses during balanced as well as unbalanced voltage conditions, applying the derating graph in Figure 6-7 to energy-efficient motors will yield conservative derating factors.



**Figure 6-7. Derating Graph and Table for Induction Motors Based Upon Percent Voltage Unbalance (from NEMA MG.1-1993)**

NEMA defines the formula for three-phase voltage unbalance as 100 times the maximum deviation of the line voltage from the average voltage of all three phases divided by the same average. Both voltage and current unbalance can be calculated using a three-step process. First, measure the phase-to-phase voltages and the currents of all three phases at the point of utilization. Second, calculate the average of the three phases. Third, determine the percent of unbalance. For example, if the measured line voltages are 462, 463, and 455 volts, then the average is 460 volts and the maximum deviation from the average is 5 volts (460 – 455). Therefore, the voltage unbalance is  $(5/460) \times 100 = 1.1$  percent.

### **6.5.2 Incompatibilities between Adjustable-Speed Drives and Motors**

As discussed earlier, the application of PWM ASDs in a process can damage conventional motors by damaging the winding insulation and by damaging the motor bearings. The National Electrical Manufacturers Association (NEMA) has developed a standard addressing performance requirements for motors applied to inverters. NEMA MG-1, Section IV, Part 31, *Definite-Purpose Inverter-Fed Motors*, specifies the requirement for squirrel-cage induction motors rated at 5000 HP or less and at 7200 volts or less, intended for use with PWM inverters. In order to address the specific concerns of transient overvoltages, the standard requires that motors that are built to this specification will have a stator insulation system that can withstand voltage pulses up to 1600 volts with a rise time greater than 0.1  $\mu$ s for motors with a base rating of less than 600 volts. Motors that conform to this specification usually employ one or more of the following additional features to augment the insulation system:

- Magnet wire with increased dielectric strength.
- Improved insulation on end turns, in the slots, and between phases.
- Heavy duty lacing taping of end-turns.
- Extra cycles of varnish dip.

There are few isolated cases where the peak voltage may exceed 1600 volts. However, insulation failure of motors that comply with the Part 31 of the standard has not been reported by end users. The problem arises from the misuse of the term “inverter-rated.” For older inverter technologies such as six-step variable-voltage source inverters, harmonic losses and the resulting motor heating were the main issues. Motors designed for accommodating the extra heat losses were labeled as inverter-duty motors. However, this did not necessarily mean an improved insulation system. The end user should clearly specify the NEMA MG-1, Section IV, Part 31 requirement for insulation systems for inverter duty motors.

Some users may prefer to use standard induction motors with ASDs to avoid the extra cost of a special motor and the expense of stocking spare motors of both types. Using properly designed filters can enable standard motors to be used with inverter applications. Typically, line reactors, RLC filters, and RC snubbers are used as the filtering devices. Some filters, such as carrier-stripping filters, have to be custom-made and are not practical for most end users. However, damped low-pass filters, which are commercially available as dv/dt filters or RLC filters, appear to be the best choice. The cost of these filters are approximately 25% of the cost of the inverter in the low-HP range (<10 HP) and approaching 5 to 10% of the inverter cost for ratings exceeding 50 HP.



As previously discussed, motors can also sustain bearing damage in ASD applications from electrical discharge machining (EDM) due to capacitively coupled shaft-to-ground voltage buildup. Once the presence of EDM has been positively identified as the root cause of bearing failure, the end user has no other choice but to take corrective actions. While there are several possible alternatives ranging from a special type of electrostatically shielded motor to ceramic bearings and/or special lubricants, the basic mitigation alternatives are to tackle the problem from the source (inverter) or from the motor side. From the inverter point of view, reducing the switching frequency and/or installing a filter are possible options. Before installing any new system, the end user should consult with the inverter manufacturer and determine if lowering the switching frequency of the inverter and/or installing a filter on the output of the inverter will reduce the rise time of the voltage pulses and solve the problem. The most effective way to ensure that this corrective action will solve the problem is to conduct a before-and-after analysis of the shaft-to-ground voltage and current analysis as shown in Figure 6-7.

From a motor standpoint, the most effective way to solve this problem is to install a shaft grounding system. This system effectively provides a low-impedance path from the shaft to the ground and minimizes the magnitude of the shaft voltage. Grounding the motor shaft with a system of brushes creates a low-impedance path to ground for otherwise damaging discharge currents. A number of brush systems are commercially available. Soft carbon brushes are not suitable because they can create a nonconductive film that prevents electrical contact between the brushes and the shaft. Brushes made of special materials, such as brass and stainless steel, do not create this film. Also, a sealed grounding system is recommended for a clean-room environment, which may be contaminated by airborne particles. During routine maintenance, ensure that the brushes are in electrical contact with the shaft, regardless of the type of grounding system.

Another possible motor-side alternative is to install insulated motor bearings. Although insulated motor bearings stop the flow of discharge current through the motor bearings, they do not prevent damage to the bearings of other shaft-connected equipment, such as tachometers and fans. The typical cost of such a system for a 200-HP motor is in the range of \$700.

## 6.6 Solutions to Grounding Problems

Grounding problems will typically manifest themselves as equipment failures. This will be most apparent in electronic solid-state devices, particularly if they are spread out over a large area and connected by data cables. A typical electronic device has one side of its circuit connected to its chassis, which is grounded through the grounding conductor in its power cord. The grounds of two devices in separate chassis may be connected with a data cable that has grounds or a shield. This configuration presents a ground loop. Ground loops may not cause a problem if there is insufficient voltage (less than 0.5 volts) between the two devices. However, damage can occur when a large enough current exists in one of the circuits to raise the ground potential of one device.

Damage to devices can also occur when the power ground has been lost. If the ground has been disconnected, ground currents will find a path to the power ground. This path may flow through circuits and devices that are not designed to withstand that current and cause damage.

Grounding can be tested by a ground-impedance tester. A ground-impedance tester is a multifunctional instrument designed to detect certain types of wiring and grounding problems in low-voltage power distribution systems. The primary test function is impedance measurement of the equipment grounding conductor from the point of test back to the source neutral-to-ground bond, as well as the impedance of the neutral conductor. This impedance should not exceed 0.25 ohms. It is also important to test the building grounding system with respect to earth ground. This should be done with a fall-of-potential test instrument during the installation of the building grounding system.

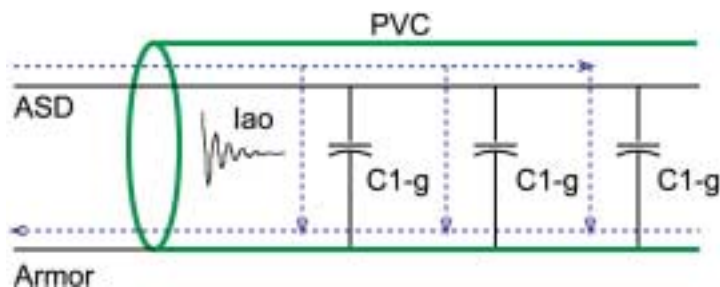
In addition to testing, checking the condition of the power and grounding system in a facility should be part of a routine preventive maintenance program. This includes checking for missing or improper ground connections, ensuring that the neutral and ground are bonded only at the power source, and checking for proper application of isolated grounds.

## 6.7 Solutions to Electromagnetic Interference Problems

There are four methods to mitigate EMI in the industrial facility: proper grounding, attenuating emissions at the source, shielding sensitive equipment, and capturing and returning emissions to the source.

### 6.7.1 Proper Grounding

The practice of using unshielded phase output wires in a cable tray from an ASD to a motor can introduce common-mode noise into the system. The use of a shielded-armor power cable from a drive to a motor will provide a path for the common-mode noise to return to the source. Figure 6-8 demonstrates this concept.



**Figure 6-8. Use of a Shielded/Armor Cable to Reduce Electromagnetic Interference**

Signal shields reduce external coupling but may introduce EMI if the shield is connected to a noisy ground potential. The standard practice is to ground the shield at the source side of the cable. If the standard practice does not eliminate the EMI, it becomes necessary to do whatever it takes to fix the problem, including grounding on both ends, grounding on the other end, or not grounding at all.

### 6.7.2 Attenuating Emissions at the Source

The best way to eliminate system emissions is to attenuate emissions at the source. The use of a common-mode choke (CMC) is one way to achieve this. A CMC is an inductor with phase A, B, and C conductors wound in the same direction through a common magnetic core. It provides high impedance and high inductance to any line-to-ground capacitive current emissions. Unlike a line reactor/inductor, a CMC does not affect the power-line circuit. This device is available from drive vendors. Figure 6-9 shows an example of a CMC application.

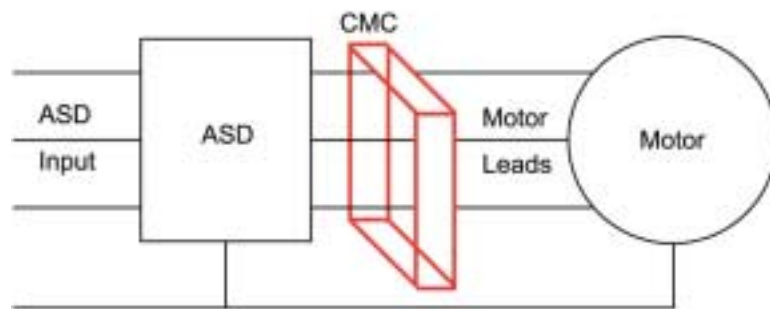


Figure 6-9. Application of a Common-Mode Choke

### 6.7.3 Shielding Sensitive Equipment

The path of common-mode emissions can be diverted from sensitive equipment. One practice is to separate control and signal cables from high-voltage wires. It is also best if the power conductors include a ground wire and are placed in a conduit. The conduit should be bonded to an ASD cabinet and motor junction box, and the ground wire should be connected to the cabinet ground bus and motor ground stud. The ground wire and conduit will absorb most of the capacitive noise and return it back to the source of emissions.

Another practice is to separate control and signal cables from power cables in cable trays. The practice of placing covers on a signal cable tray will further reduce the noise coupled to the signal cables from the power cables.

### 6.7.4 Capturing and Returning Emissions to the Source

Another method to reduce EMI is to capture emissions and return them to the source. This can be accomplished with an EMI filter. Figure 6-10 demonstrates the use of an EMI filter. This figure shows that the CM current  $I_{ao}$  will collect in the ground conductors and return to the drive through the EMI filter. The filter contains a large common-mode core inductance and individual phase inductors that limit the high-frequency, series-ground return current to low levels in the main AC supply. The filter also contains line-to-ground capacitors to reroute most of the high-frequency ground emissions back to the AC drive input terminals.

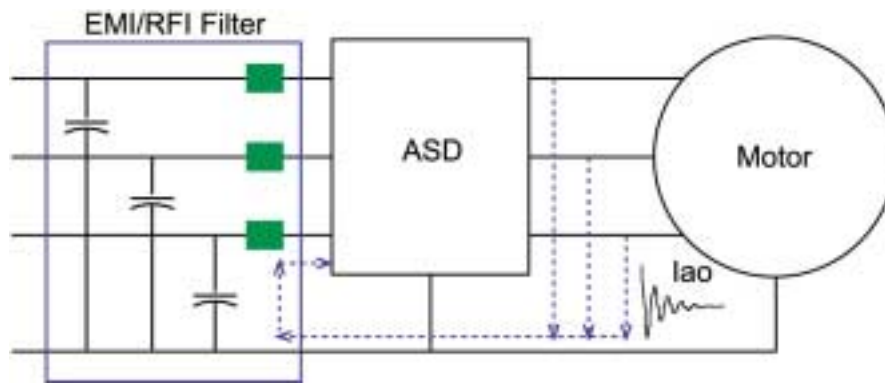


Figure 6-10. Application of EMI Filter

# 7

## CHECKLIST FOR EQUIPMENT FAILURE

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Electrical disturbances are not the only sources for equipment failure. The checklists in Tables 7-1, 2, and 3 can help you determine the cause of failure for some of the equipment discussed in this guide.

**Table 7-1. Causes of Motor Failure**

Manufacturing Defect
High Ambient Temperature
Foreign Material
Water in Motor
Inadequate Ventilation
Winding Failure
Locked Rotor
Overload
Over-Greasing
Ground Fault
Bearing Failure
Transient Overvoltage
ASD Output Voltage
Voltage Phase Unbalance

**Table 7-2. Causes of ASD Trips**

Operator Action
Process Computer Error
High Ambient Temperature
Ground Fault
Restricted Ventilation
Voltage Sag
Electromagnetic Interference
Transient Overvoltage

**Table 7-3. Causes of Erratic Operation of Controls**

Damaged Control Wire Insulation
Damaged Critical Sensor
Loose Connection
Software Problem
Voltage Sag
Electromagnetic Interference
Current Harmonics



# 8

## SUMMARY

Power quality problems can disrupt facility and process loads in many ways. With sufficient knowledge of the causes of these problems, steps can be taken to mitigate or eliminate their effects. This guidebook has presented the most common power quality problems that are experienced in industrial facilities, as well as potential solutions for these problems. Table 8-1 summarizes the typical power quality problems and potential solutions covered in this guidebook.

**Table 8-1. Power Quality Problems and Solutions**

<i>Type of Solution</i>	<i>Applications</i>	<i>Cost</i>
<b><i>Voltage Sags</i></b>		
Ferroresonant Transformer	Primary advantage is that this device is maintenance free. Typically applied to single-phase loads. Most applications are for circuit control circuits or computer loads. Should be sized for maximum inrush current. Size the transformer at twice the load for best sag protection.	Relatively low cost
Uninterruptible Power Supply (UPS)	Typically applied to single-phase devices. Typical loads are control circuits, PLCs and computers. Often applied when interruptions are an issue.	Moderate cost
Reprogramming	Applied to ASDs. ASD can be reprogrammed for flying restart or timed delay restart. The undervoltage trip point can also be reprogrammed.	Low cost. Software change.
Dip Proof Inverter	Typically applied to single phase loads. Applied to ASDs, control circuits, and PLCs. Provides one second of ride through when sized for load. Provides two seconds of ride through when sized for twice the load.	Moderate cost
Written Pole Motor Generator	Can be applied for three phase loads up to 500kW. Can supply power for up to 15 seconds during an interruption.	
Superconducting Magnetic Energy Storage (SMES)	Applied to entire facility. Can produce several megawatts for seconds.	Approximately \$1000/kW
PQ2000	Applied to entire facilities. Can produce up to 2 MVA for 15 seconds.	

Table 8-1 (con't)

Type of Solution	Applications	Cost
<b>Capacitor-Switching Transients</b>		
Line Reactors	Typically applied with ASDs. Most common size is 3% of ASD/motor size.	
Incremental Switching	Utility solution accomplished by installing individual breakers on each step.	Utility cost
Capacitor Bank Line Reactors	Utility solution to install reactors in series with capacitor banks.	Utility cost
Synchronous Switching	Utility solution to synchronize switching with zero crossings .	Utility cost

Type of Solution	Applications	Cost
<b>Surges</b>		
Lightning arrestors	Applied in substations and switchyards to divert lightning to ground before entering facility.	
Transient Voltage Surge Suppressor (TVSS)	Panel mounted devices can protect all loads fed from panel from external surges. Individual TVSSs can be applied at sensitive loads.	

Type of Solution	Applications	Cost
<b>Harmonics</b>		
Harmonic filters	Filter should be tuned to the lowest significant harmonic present. Harmonic study should be performed prior to implementation.	
Isolation transformers	Typically applied to ASDs. Zero sequence harmonics generated by drive cannot pass through isolation transformer. Transformer also provides reactance to attenuate other harmonics.	
Line reactors	Typically applied to ASDs. Reactance will attenuate harmonics generated by drives.	
Isolation	Feeding sensitive loads and harmonic loads from separate sources provides greater system impedance between loads.	Low cost

Type of Solution	Applications	Cost
<b>Voltage Unbalance</b>		
Balance single-phase loads	Measure loading on each phase and move single phase loads to other phases to achieve balance.	
Derate motors	Motors must be oversized to compensate for voltage imbalance.	



Table 8-1 (con't)

<i>Type of Solution</i>	<i>Applications</i>	<i>Cost</i>
<b><i>Electromagnetic Interference (EMI)</i></b>		
Shielded armor power cable	Use of shielded power cable on ASD output cable will reduce EMI. Typically, shield should be grounded.	
Common mode choke (CMC)	Available from drive vendors. CMC will attenuate ground based capacitive noise current.	
Shield and separate signal cable	Do not run signal cable in same cable tray as power cable. Put signal cable in separate cable tray with covers.	
EMI/RFI filter	Filter will capture noise and return it to drive.	



# 9

## ONLINE SOURCES OF POWER QUALITY INFORMATION

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- Allen Bradley web site containing published results of power quality research.  
<http://www.ab.com/drives/techpapers/ieee/ieee.html>
- Power Quality Assurance Magazine on-line.  
<http://www.powerquality.com/>
- Manufacturer list of power and power quality products.  
<http://www.reade.com/TSI/manufacturers.html>
- Power quality news items.  
<http://www.darnell.com/02-pqp.stm>
- Interactive power quality training course.  
<http://www.virtualelectrician.com/Main.htm>
- Source of power quality information from Robicon.  
<http://www.robicon.com/library/>
- Research center in Australia.  
[http://www.elec.uow.edu.au/pqc/pq\\_pub.html](http://www.elec.uow.edu.au/pqc/pq_pub.html)
- Utility-based information source.  
[http://www.pge.com/customer\\_services/residential/powerqual.html](http://www.pge.com/customer_services/residential/powerqual.html)
- Power quality research center started by the Electric Power Research Institute, source of publications and ongoing research news.  
[www.epri-peac.com](http://www.epri-peac.com)
- Information on application of isolation transformer.  
<http://www.signaltransformer.com/signal/techlib/techlib.cfm>
- Technical articles on PQ issues with motors.  
<http://www.mastercontrols.com/EngInfo/MCEngInf.htm>
- Technical articles from DOE on application of back-up generators.  
<http://www.dp.doe.gov/CTG/bpwg/bpwg.htm>
- Power quality articles from Electrical Construction and Maintenance (EC&M) Magazine website.  
<http://www.ecmweb.com/articlesfree.htm>

- General information on power quality.  
<http://www.electricalzone.com/home.asp>
- Information on power quality from Plant Engineering Magazine.  
<http://www.manufacturing.net/magazine/planteng/>
- Application Notes from Lutron on power quality issues with lighting loads.  
<http://www.lutron.com/applicationnotes/Default.htm>
- Links related to energy-storage technologies.  
<http://www.etis.net/link/Storlink.html>
- Technical library from JT Packard on Uninterruptible Power Supplies (UPS).  
<http://www.jtpackard.com/library.html>
- Application notes and case studies from Dranetz-BMI Library.  
<http://www.bmi-dranetz.com/>
- Power quality case studies from the Copper Page .  
<http://powerquality.copper.org/>
- Technical articles on power quality from MTE Corporation.  
<http://www.mtecorp.com/#custom1>
- Interpretation and analysis of power quality measurements.  
<http://www.pqnet.electrotek.com/pqnet/main/backgrnd/tutorial/measure/paper/paper.htm>
- Power quality glossary from Teal Corporation.  
<http://www.teal.com/glossary.html>
- Power quality standards webpages.
  - IEEE Working group areas  
<http://grouper.ieee.org/>
  - Monitoring Electric Power Quality  
<http://grouper.ieee.org/groups/1159/>
  - Voltage Sag Indices  
<http://grouper.ieee.org/groups/sag/>
  - Power Quality Standards Coordinating Committee  
<http://grouper.ieee.org/groups/scc22/>
  - Power System Compatibility with Electronic Process Equipment  
<http://grouper.ieee.org/groups/1346/index.html>

- IEEE Harmonics Working Group  
<http://grouper.ieee.org/groups/harmonic/index.html>
- IEC Power Standards  
<http://ftp.iec.ch/>
- Voltage sag standard for semiconductor equipment  
<http://www.semi.org/nav/index.shtml>
- CBEMA/ITIC Voltage sag tolerance curve for equipment  
<http://www.itic.org/technical/iticurv.pdf>



